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CAPSTONE PROJECT

Tactical Satellite (TacSat) Feasibility Study
A Scenario Driven Approach

by

Ryan Davis, Jennifer Gordon, Catherine Jose, Roy Kyser, Stephen May, Nguyen Anh, Maria Olea, Robert Perkins, Jose Reyes, Fredric Scali, Robert Vik, Vinoj Zachariah, Uriah Zachary, Mauricio Zubieta-Hernandez

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Capstone Project Advisor:	John M. Green
Second Reader:	Daniel E. Cunningham

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COL. David A. Smarsh, USAF
Acting President

Leonard A Ferrari
Associate Provost

This report was prepared for the Chairman of the Systems Engineering Department in partial fulfillment of the requirements for the degree of Master of Science in Systems Engineering.

This report was prepared by the Masters of Science in Systems Engineering (MSSE) Cohort Four from the Space and Naval Warfare Systems Center, San Diego:

Authors:
Davis, Ryan ______________________
Gordon, Jennifer ______________________
Jose, Catherine ______________________
Kyser, Roy ______________________
May, Stephen ______________________
Nguyen, Anh ______________________
Perkins, Robert ______________________
Reyes, Jose ______________________
Scali, Fredric ______________________
Vik, Robert ______________________
Olea, Maria ______________________
Zachariah, Vinoj ______________________
Zachary, Uriah LCDR/USN ______________________
Zubieta-Hernandez, Mauricio ______________________

Reviewed by:

____
David H. Olwell, Ph. D.
Chairman, Department of Systems Engineering

Released by:

____
Dan C. Boger, Ph. D.
Interim Associate Provost and Dean of Research

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Davis, Ryan	Perkins, Robert
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Jose, Catherine	Scali, Fredric
Kyser, Roy	Vik, Robert
May, Stephen	Zachariah, Vinoj
Nguyen, Anh	Zachary, Uriah LCDR/USN
Olea, Maria	Zubieta-Hernandez, Mauricio

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Monterey, CA 93943-5000

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13. ABSTRACT

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LIST OF ACRONYMS

ACINT	Acoustic Intelligence
ACTD	Advanced Concept Technology Demonstration
AD&C	Attitude Determination and Control
ADCS	Attitude Determination and Control Subsystem
AFRL	Air Force Research Laboratory
AFSC	Air Force Systems Command
AFSCN	Air Force Satellite Control Network
AFSPC	Air Force Space Command
AJ	Anti-Jam
AoA	Analysis of Alternatives
AOR	Area of Responsibility
APL	Applied Physics Lab
ARES	Affordable Responsive Spacelift
AS	Anti-Scintillation
AS&C	Advanced Systems and Concepts
ASD	Assistant Secretary of Defense
ASPO	the Army Space Program Office
ASUW	Anti-Surface Warfare
ASW	Anti-Surface Warfare
AUS	Australia
BAS	British Antarctic Survey
BFT	Blue Force Tracking
C&DH	Command & Data Handling
C&DH	command and data handling
CAN	Canada
CDL	Common Data link
CDLS/MIST	Common Data Link System/Multi-Band Integrated Satellite Terminal
CDR	Critical Design Review
CDRs	Commanders
CER	Cost Estimating Relationship
CHEM-BIO	Chemical and Biological
COCOMS	Component Commands
COMINT	Communications Intelligence
COMSEC	Communications Security
CONOPS	Concepts of Operations
COTM	Comms-on-the-Move
COTS	Commercial-Of-The-Shelf
DADS	Deployable Autonomous Distributed System

Data-X	Data Exfiltration
DoD	Department of Defense
ELINT	Electronic Intelligence
EMSS	Enhanced Mobile Satellite Service
ESA	Electronically Steerable Array
FLTSATCOM	Fleet Satellite Communications System
FOV	Field of View
GAO	Government Accountability Office
GEO	Geostationary Orbit
GIG	Global Information Grid
GMTI	Ground Moving Target Indicator
GOTS	Government-Of-The-Shelf
GPS	Global Positioning System
GUI	Graphical User Interface
HEO	Highly Elliptical Orbit
IA&T	Integration, Assembly and Test
ICD	Interface control document
IDaD	Internal Defense and Development
IMINT	Imagery Intelligence
INP	Innovative Naval Prototype
IPT	Integrated Product Team
ISR	Intelligence, Surveillance, and Reconnaissance
JHU	Johns Hopkins University
JROC	Joint Requirements Oversight Council
JTF	Joint Task Force
JTRS	Joint Tactical Radio System
LAT	Latitude
LEO	Low Earth Orbit
LONG	Longitude
LOOS	Launch and Orbital Operations Support
LPD	Low Probability of Detection
LPI	Low Probability of Intercept
MANS	Microcosm Autonomous Navigation System
MILSTAR	Military Satellite Communications
MIST	Mobile Interoperable Service Terminal
MMA	Microwave Model Assembly
MOP	Measure of Performance

MSSE	Master of Science in Systems Engineering
MUA	Military Utility Assessment
MUOS	Mobile User Objective System
NAFCOM	NASA/Air Force Cost Model
NAVNETWARCOM	Naval Network Warfare Command
NGA	National Geospatial Intelligence Agency
NGO	Non Governmental Organization
NiCd	Nickel Cadmium
NIMA	National Imagery and Mapping Agency
NPS	Naval Postgraduate School
NPSA	Navy Space Field Activity
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NSSO	National Space Security Office
NZ	New Zealand
O&M	Operations and Maintenance
OFT	Office of Force Transformation
OMB	Office of Management and Budget
ONR	Office of Naval Research
ORS	Operationally Responsive Space
OSD	Office of Secretary of Defense
PM	Program Management
R&D	Research and Development
RAAN	Right Ascension of the Ascending Node
RF	Radio Frequency
RFI	Request for Information
RLSP	Air Force Rocket System Launch Program
RJ	Rivet Joint
SAA	South Atlantic Anomaly
SAR	Synthetic Aperture Radar
SATCOM	Satellite Communication
SDI	Strategic Defense Initiative
SE	Systems Engineering
SGLS	Space Ground Link Subsystem
SHF	Super High Frequency
SIGINT	Signals Intelligence
SIPRNET	Secret Internet Protocol Router Network
SMAD	Space Mission Analysis and Design
SMC	Space and Missile Command
SSC	Space and Naval Warfare Systems Center

SSCM	Small Satellite Cost Model
STK	Satellite Tool Kit
STRATCOM	Strategic Command
SVLCM	Spacecraft/Vehicle Level Cost Model
TacSat	Tactical Satellite System
TARS	Tactical Aerial Reconnaissance System
TDRS	Track and Data Relay Satellites
TELINT (RADINT)	Telemetry Intelligence
TENCAP	Tactical Exploitation of National Capabilities
TSAT	Transformation Satellite
TT&C	Telemetry, Tracking, & Command
TTCP MAR	The Technical Cooperation Program Maritime
UAV	Unmanned Autonomous Vehicle
UHF	Ultra High Frequency
UK	United Kingdom
U.S.	United States of America
USAF	United States Air Force
USECAF	Under-Secretary of the Air Force
USSTRATCOM	U.S. Strategic Command
VAB	Van Allen Belts
VMOC	Virtual Mission Operation Center
WBS	Work Breakdown Structure
WGS	Wideband Gap Filler

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EXECUTIVE SUMMARY

The objective of this project was to examine the cost and operational feasibility of developing a tactically controlled, operationally responsive satellite system. The approach made use of systems engineering practices based on the Space Mission and Analysis and Design (SMAD) process. [Larson W, Wertz J 1999] A specific mission scenario, the Philippine Sea Scenario, was chosen to guide and bound the analysis. The scenario led to military requirements that drove the requirements for the space mission. These high level mission requirements were devolved into space system requirements by conducting a gap analysis to see which of the military requirements were not well served by existing tactical system such as Global Hawk. Appropriate payloads, orbits, and constellation sizes were then selected to meet these requirements. These in turn drove the development of a common bus concept. The concept of operations (CONOPS) and ground infrastructure to support such a mission were also examined. This high level space systems engineering exercise provided insights into operations and military utility as well as estimated costs for such a system.

The orbits that have the most utility are in Low Earth Orbit (LEO) between 400 and 500 kilometers. Constellation sizes between two and four satellites provided acceptable coverage and revisit times.

The Virtual Mission Operations Center (VMOC) concept gives tactical control of the TacSat payload while spacecraft operations and mission control require a globally distributed ground infrastructure. Additional TacSat infrastructure is also required for the launch facilities including pre-staged launch vehicles, payloads, and buses. The cost of this infrastructure can be minimized by using existing Air Force ground stations and operations facilities.

The natural shelf life of spacecraft and launch vehicles as well as the need to train as we fight requires that there be regular launches of TacSats. This will lead to regular yearly costs associated with the TacSat program but will drive down per unit costs as

more satellites are produced. This should also encourage more rapid development of and space qualification of new satellite technologies.

The procurement and operational costs of a TacSat system are estimated to be about $65 million for a constellation of two satellites. Operations costs of a tactical satellite system can be significantly less than the Global Hawk system when operated continuously over a one- to two-year period.

The study shows that there are tactical scenarios in which space capabilities provide military utility and cost effectiveness above what is provided by traditional tactical assets such as UAVs. This is particularly true when large operational areas are involved and long periods of service are required.

1.0 INTRODUCTION

This study is a product of students enrolled in the Naval Postgraduate School (NPS) Master of Science in Systems Engineering (MSSE) program (Space Systems Emphasis). This group project is sponsored by Space and Naval Warfare Systems Center (SSC) San Diego, the National Space Security Office (NSSO), and the Navy Space Field Activity.

1.1 THESIS STATEMENT

Tactical Satellite (TacSat) is an operationally responsive and cost effective satellite system concept that can provide effective intelligence, surveillance, reconnaissance, and communications support to tactical commanders and warfighters.

1.2 BACKGROUND

The U.S. Department of Defense (DoD) is building a series of tactical satellite demonstrations that will be launched and tested over the next several years. If successful, some of the key concepts, such as rapid launch timelines, standards-based bus designs, payloads composed of commercial-of-the-shelf (COTS) and government-of-the-shelf (GOTS) sub-systems, and direct Secret Internet Protocol Router Network (SIPRNET) connectivity, will fold into a new DoD acquisition effort called Operationally Responsive Space (ORS). Some background on the TacSat and ORS efforts is useful to understand the relationships of the various programs and understand the importance of this thesis project.

Small satellites, typically defined as those with a launch weight of less than 1,000 lbs, have historically been limited to the domain of university efforts and modest Research and Development (R&D) projects. Technological advances in satellite materials and micro-electronics over the last 15 years, however, have led to increasingly capable university designs that have captured the interest of military payload planners. Parallel advances in rocket fabrication and propulsion technologies led to renewed interest in the idea of a new family of less-costly, modular launch vehicles. In 2003, the

Air Force Space Command (AFSC) funded an Operationally Responsive Spacelift Analysis of Alternatives (AoA) to find an optimal design for such a family of launch vehicles. The Air Force's goal is to significantly reduce the per-pound cost to orbit while at the same time dramatically reducing the time from launch call-up to on-orbit availability. The results of this study have led to several new launch vehicle programs, including the DARPA/U.S. Air Force FALCON demonstration program and the Air Force's Affordable Responsive Spacelift (ARES) development program.

Nearly in parallel with the ORS AoA, the Office of the Secretary of Defense's (OSD's) Office of Force Transformation (OFT) seeded a collaborative initiative to investigate and demonstrate the military utility of small satellites that could be launched rapidly, with direct SIPRNET connectivity, in response to emerging tactical requirements. This first OFT initiative, TacSat-1, has been led by the Naval Research Laboratory (NRL).

Shortly following the ORS AoA and the kick-off of TacSat-1, then Under-Secretary of the Air Force (USECAF) Peter B. Teets endorsed an aggressive plan to initiate an overlapping series of TacSat demonstration projects, one each year, to test the technical feasibility, affordability, and battlefield utility of small satellites that could be stockpiled and managed as tactical military reserve material. About this same time, the AFSC led the development of an Advanced Concept Technology Demonstration (ACTD) proposal, dubbed TacSat-2, to convert a small satellite S&T effort, named Roadrunner, at the Air Force Research Laboratory (AFRL) into military utility demonstration. The Office of Naval Research (ONR) and the Army Space Program Office (ASPO) joined the ACTD effort, which was approved by the Joint Requirements Oversight Council (JROC).

Shortly after the Teets-endorsed TacSat schedule was announced, OFT, AFRL, and the Air Force Space and Missile Command (SMC) established a 4-phase ORS Standard-bus program that would produce the bus designs for TacSat-3 and TacSat-4. Meanwhile, AFSC organized a joint, ad-hoc TacSat Requirements IPT to establish a TacSat mission and payload selection process for TacSats-3, -4, -5, and -6 that included input and critique by the various U.S. Component Commands (COCOMS).

This early flurry of ORS organization in the 2004 timeframe has led to a number of ORS accomplishments in the last two years. TacSat-1 is complete at NRL and awaiting launch on a FALCON launch vehicle in 2007. TacSat-2 is in final system tests at AFRL and awaiting launch on an Minotaur in late 2006 or early 2007. The TacSat-3 standard-bus design, payload selection, and contracts awards have been accomplished, and TacSat-3 is under construction at AFRL. The ORS Standard Bus effort is now focused on TacSat-4. The TacSat-4 payload selection was accomplished, and the design is now at Critical Design Review (CDR). The ORS Requirements IPT has initiated a TacSat-5 mission selection process. AF SMC continues both the ARES studies and an on-going ORS Common Bus effort, looking at a family of modular bus designs for several classes of ORS payloads. On the programmatic front, both the House and Senate Armed-Services Committees have approved funding for a DoD ORS Program of Record start in 2008.

A summary of the four TacSat demonstrations currently underway is useful to understanding the context for this thesis project. For an excellent overview of the TacSat missions and ORS program development, see “A TacSat and ORS Update Including TacSat-4” [Doyne, 2006].

TacSat-1 is sponsored by OFT and managed by NRL. NRL is also the lead developer. It is scheduled to be launched on the second flight of the SpaceX Falcon-1 launch vehicle, likely in early 2007. The overall objective of TacSat-1 has been to catalyze DoD and industry toward consideration of small, low-cost satellites and launch vehicles as a viable military capability. The key elements of the TacSat-1 mission include a militarily-useful microsatellite, a low-cost launch vehicle, and direct SIPRNET access via a web-based Virtual Mission Operations Center (VMOC) for tasking, data dissemination, and collaboration. The payload consists of a Radio Frequency (RF) sensor, a visible and infrared imager, and a direct tactical UHF link for EP-3 and, later Rivet Joint (RJ), aircraft for cross-platform mission use. Tasking modes, VMOC operation, and TacSat-1 simulation approaches can be found in the Experimentation Plan (EXPLAN) For Terminal Fury 06 CPX Initiative: TacSat-1 Operations, December 2005 [EXPLAN, 2005].

The TacSat-2 ACTD is managed by AFRL, who is also the lead developer. It is co-sponsored by AFRL, AFSC, the Air Force Space Test Program (STP), ONR, ASPO, and the Assistant Secretary of Defense (ASD) for Advanced Systems and Concepts (AS&C). The ACTD is sponsored by the U.S. Strategic Command (USSTRATCOM). TacSat-2 is scheduled for a Minotaur launch in late 2006 or early 2007. Having grown out of the Roadrunner space technology program, it retains many of the original Roadrunner experiments, including an On-board Autonomy experiment and experimental Hall Effect thrusters. The ACTD payload suite includes the Target Indicator Experiment (TIE, an RF sensor payload similar to the RF payload on TacSat-1), a multi-spectral optical imager, and a Common Data link (CDL) communications system. Like TacSat-1, TacSat-2 tasking and data dissemination includes the SIPRNET VMOC. TacSat-2 offers additional communications, however, with the first space-borne CDL, which will transit multi-color tactical imagery to an Army Mobile Interoperable Service Terminal (MIST) at 274 Mbps. Pan-imagery and TIE data will be able to be transmitted either via CDL or via the S-Band Space Ground Link Subsystem (SGLS). The TacSat-2 ACTD will focus on operational demonstration and military utility assessment (MUA) of the tactical satellite concepts.

TacSat-3 was the first TacSat with a mission focus selected through the joint TacSat Requirements IPT process. A hyperspectral imaging concept was selected, and is sponsored by the Army and by AFRL. TacSat-3 is managed by AFRL. OFT is funding the satellite bus as part of the ORS Standard Bus effort. TacSat-3 will also carry a small tactical data exfiltration (Data-X) payload, funded by ONR. Like TacSat-2, TacSat-3 will carry a CDL communications payload for transmitting hyperspectral imagery data to tactical image analysts. TacSat-3 is expected to be complete by mid-2007 and launched in late 2007 or early 2008. The Army and USSTRATCOM are leading the CONOPS development and tactical demonstration plans. For additional info on TacSat-3, see "Development of the Tactical Satellite 3 for Responsive Space missions" [Davis, 2006].

TacSat-4, also selected through the TacSat Requirements IPT process, is being developed as separate bus and payload development efforts, using a standards-based interface control document (ICD) as the medium between the two teams. The bus is funded by OFT as part of the ORS Standard Bus effort, and co-managed by NRL and the

Johns Hopkins University (JHU) Applied Physics Lab (APL). The payload is funded by ONR under the TacSat Innovative Naval Prototype (INP) Program and managed by NRL. TacSat-4 will carry a tactical communications payload in a 4-hr, highly elliptical orbit, allowing substantial dwell time over a theater. The UHF communications payload will support Comms-on-the-Move (COTM), Blue Force Tracking (BFT), and Data-X, with a focus on providing augmented UHF Satellite Communication (SATCOM) capacity to unattended sensor systems, emergent tactical requirements and underserved regions. The TacSat-4 launch is being planned for late 2008 as part of the new Air Force Rocket System Launch Program (RLSP).

1.3 PURPOSE

There are many technical challenges unique to the development of tactical space systems and there are many concept of operations (CONOPS) issues that remain unresolved. The word "tactical" itself has many different meanings among defense community representatives. Decision makers in all the services are grappling with these issues as they decide whether or not to move forward with the tactical space concept.

It is the intention of this study to 1) capture in one place key operationally responsive space relevant information and 2) conduct a feasibility analysis using sound systems engineering techniques and principles.

1.4 SCOPE

This thesis will bound its analysis and provide it greater relevancy by conducting it within a specific mission scenario. The high level mission objectives, requirements, and constraints for a tactical space system are all derived from the Philippine Sea Scenario. (Appendix C) All aspects of military and associated civilian operations such as humanitarian relief will be considered in scope for this scenario.

1.5 PROCESS

The System Engineering process for this study includes requirements analysis, functional requirements decomposition, and system concept design analysis. The

requirements analysis section of the study serves to initially bound the analysis and provide greater relevancy by conducting operational requirements analysis within a specific mission scenario. Bounded by this scenario, subsequent sections of this study develop the high level objectives and mission requirements.

Based on the requirements analysis, functional requirements decomposition is performed to determine system level design requirements. After functional requirements are identified, alternatives are examined to determine which of these are best satisfied by a tactical space mission rather than traditional national missions or tactical capabilities such as those provided by UAVs. The gaps identified in this analysis identify a handful of missions that are best satisfied by a tactical space mission.

The systems analysis section references the space mission requirements resulting from the gap analysis and further breaks them down into system level requirements for a possible tactical space system. This system engineering process then identifies candidate payloads and orbits. This is followed by a determination of certain key system parameters such as payload volume, mass, power requirements and pointing and stabilization requirements for the proposed payloads. Orbital parameters further determine key parameters for the power system such as length and frequency of eclipse periods. With these data points in hand high level models are developed that describe key aspects of the space system. These are the mass, volume, and power budgets. This level of systems analysis provides the input data for cost estimating relationships to predict cost of the TacSat system. The cost estimating relationships used for this study are part of the small satellite cost model provided by Aerospace Corporation.

Special emphasis is placed on the assessment of TacSat payloads and constellations. Payloads considered include communications, unattended sensor data relay, panchromatic imagery, hyper-spectral imagery, and Signals Intelligence (SIGINT). The analysis of the TacSat bus, launch vehicle, and ground station will be limited to those attributes necessary for total system analysis.

Figures 1-1 and 1-2 illustrate the systems engineering processes used for this study. Figure 1-1 illustrates the overarching system engineering process including mission objectives, CONOPS, alternatives, gap analysis, and system concept analysis.

Figure 1-2 illustrates the details of the systems concept analysis process. This was the core process used to define the proposed system design.

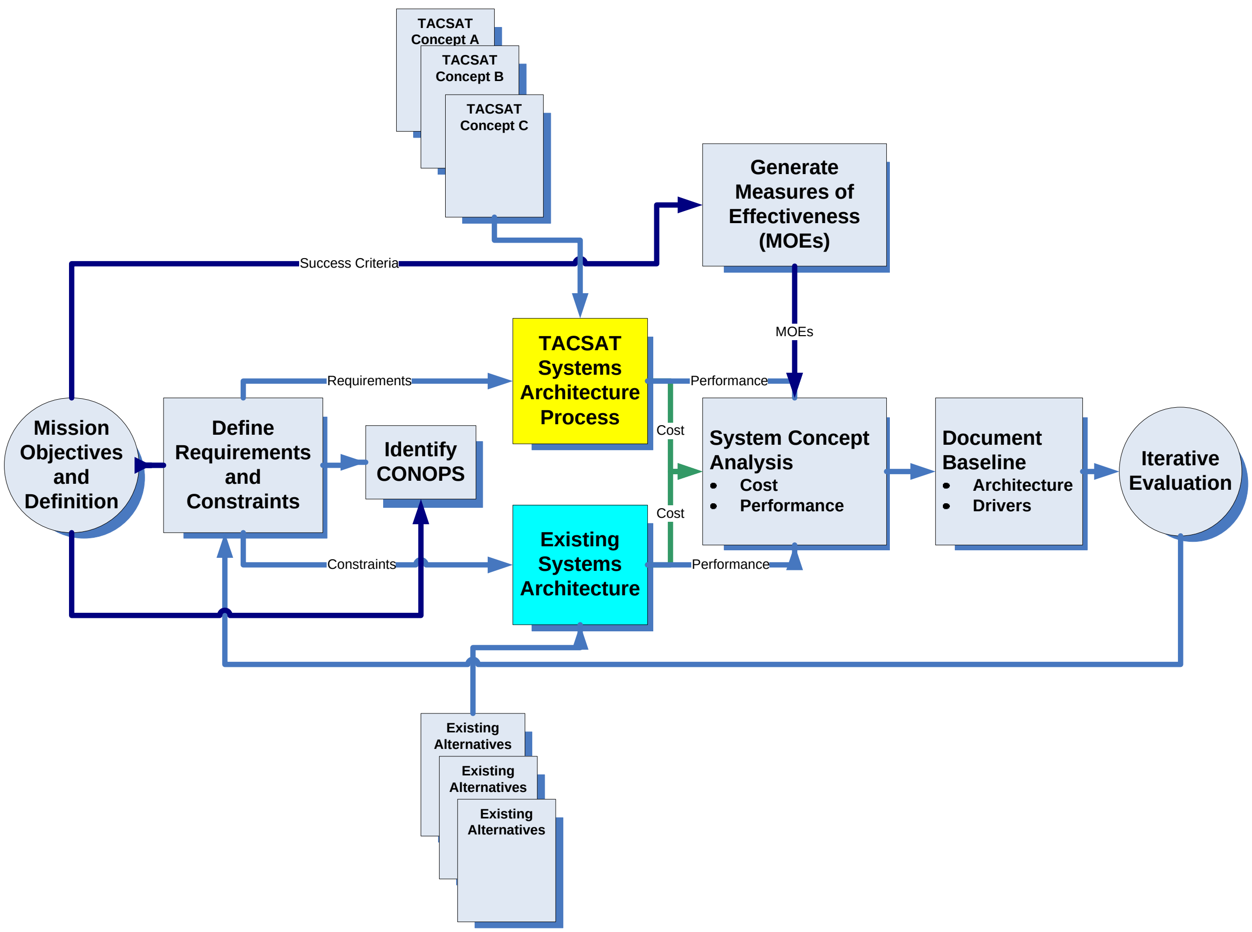

Figure 1-1. Overarching SMAD System Engineering Process

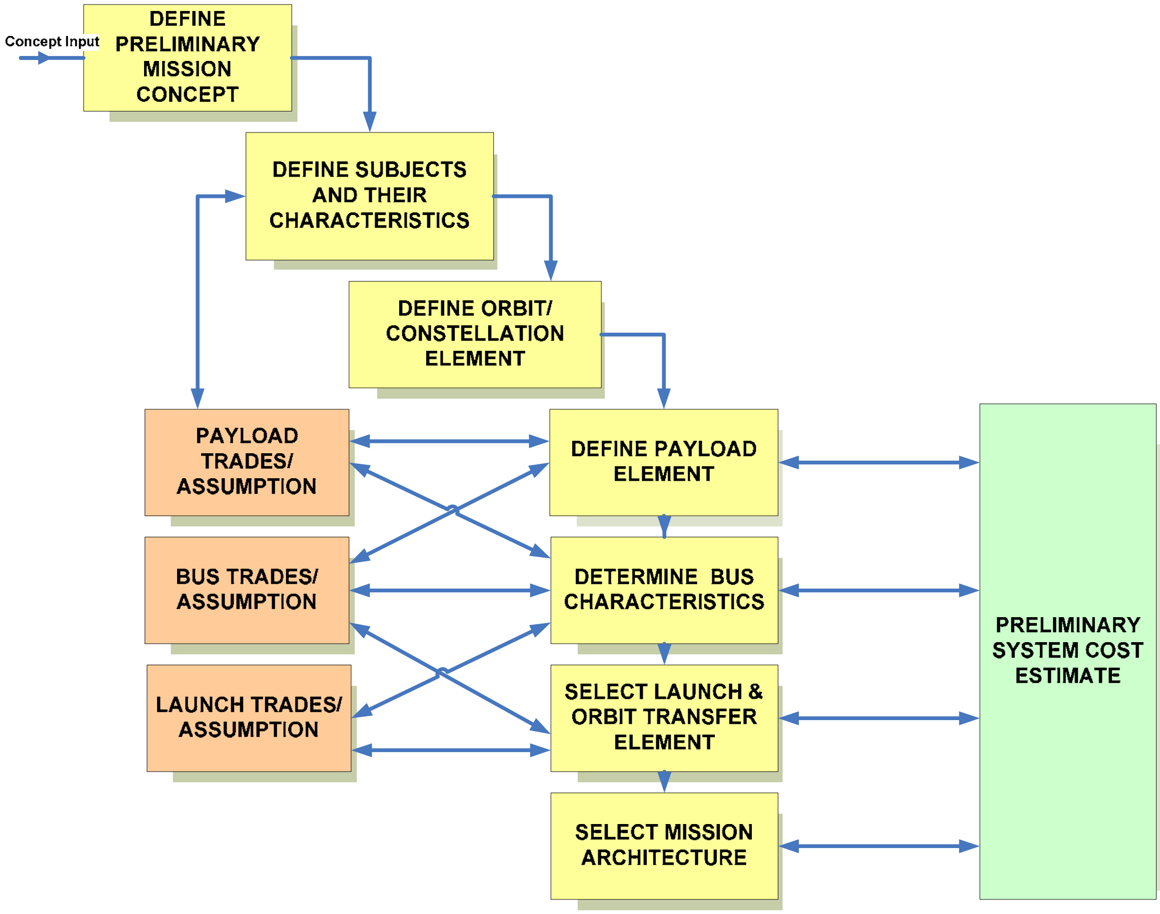

Figure 1-2. Detailed System Concept Analysis Process

2.0 MISSION DEFINITION

2.1 MISSION NEED

National space assets, downscaled at the end of the cold war, will continue to be oversubscribed by a combination of bandwidth consuming systems, increasing numbers of users, and increasing worldwide demand. Increasing demands for high resolution imagery and streaming video combined with the growing numbers of users exceed the capacity of current and planned systems. Furthermore, data from sensor to end-user can be time consuming, as can the process for sensor tasking. Prioritization of the Request for Information (RFI) at the national level often leaves the tactical commander at the end of the line. As the sensor to shooter timeline decreases, the need for the tactical user to have direct control and fast response from remote sensors increases.

Along with increasing demands, denial of service issues will also grow with time. The capability of foreign powers to target, damage, or destroy national assets will continue to increase. All space-based systems are subject to damage from natural, unpredictable cosmic events that could also preclude timely access to services. U.S. Forces' survival depends upon primary and backup Intelligence, Surveillance, and Reconnaissance (ISR), weather and communications from space.

As a result the DoD Joint and Coalition Forces have a growing mission need for highly-responsive overhead sensor and communication systems. These systems will augment current assets and serve as temporary replacements for national assets.

2.2 SCENARIOS

The scenario for this study is the Coalition FORCEnet Study – Operation Philippine Comfort Scenario. It was developed by The Technical Cooperation Program Maritime (TTCP MAR) Group/Action Group 6 to study the coalition impact of participating in the USN FORCEnet program. The intention of the scenario is to provide guidance to each Nation (US/AUS/CAN/NZ/UK) in terms of identifying opportunities to participate in FORCEnet, and the operational benefits that might result. The aim is to assist each Nation's decision making process, by supporting their criteria for evidence to

approve such an investment. The intention of using this scenario for this study is to show the possible impact of TacSat on coalition operations and to show the integration points between TacSat and FORCEnet. The movement of data to and from TacSat will be based on the principles outlined in FORCEnet.

The scenario in its entirety in contained in Appendix C. It contains elements that allow for the exercising of various Coalition mission sets, including Humanitarian Assistance/Disaster Recovery, Force Projection, Force Protection, Anti-Insurgency Operations and Geopolitical Stabilization. All of these missions benefit from space-based assets and provide a model background for examining the feasibility of a TacSat program.

2.3 THREATS

Threats derived from this scenario include natural threats, political threats, symmetric military threats, and asymmetric threats. This combination of symmetric and asymmetric threats is not unique and this study shows that Tactical Satellites can minimize these threats.

Natural threats include ever present threats posed by the environment such as weather phenomena and the unique threats from the volcanic eruptions which include the localized immediate danger of pyroclastic flow as well as wide-spread long term danger of dust/debris fallout. This study will examine whether TacSat will minimize the impact of environmental disasters by providing rapid updates of volcanic activity and the associated destruction to decision makers in the region. TacSat could assist rescuers by providing frequent imagery updates as they search for disaster survivors and trek into regions where all terrain has been destroyed and altered to the point where available maps are no longer useful.

Political threats include the destabilization and change of governments within the region as well as the threats posed by competing countries involvement (e.g. China, Russia) in the region and political affairs. TacSat could address these threats by providing movement reports of all activity in the region of interest.

Military threats include the military forces of Indonesia, the “insurgents”, and the possible indirect interference from other countries. Military threats include diesel-electric submarines, small surface combatants, combat aircraft, and land warfare threats such as truck loaded rockets. The military order of battle is detailed in the scenario (Appendix C). TacSat may support managing these threats by providing imagery for widely dispersed targets and with revisit rates unattainable by current systems. TacSat can also provide persistent data relay capability for large scale undersea sensors and ground sensors.

Asymmetric threats include terrorist activities from the rebels in the Southern Philippines. This study assumes the hypothesis that “the four principles of Internal Defense and Development (IDaD) as currently defined in U.S. Joint Doctrine (1) maximum intelligence, (2) minimum violence, (3) unity of effort, and (4) responsive government are the applicable variables in defeating the modern asymmetric threat”. [Connor, Robert J. Captain, United States Army (2002)] This study demonstrates TacSat provides a vital and unique intelligence capability to support “maximum intelligence”. By employing TacSat within the FORCEnet construct, TacSat helps provide “unity of effort” through near real-time intelligence sharing across the battlefield.

2.4 ENVIRONMENT

The environment needs to be characterized with respect to both indo-atmospheric and exo-atmospheric factors. As a low cost system TacSat needs to carefully consider environmental factors in order to maximize performance and minimize design, development, and operational costs. Environmental factors affect satellite design, development, construction, launch, sensor performance, orbital characteristics, and disposal. This paper will address only those issues unique to TacSat, Global Hawk, commercial satellite systems, or the mission as defined in the Philippine scenario. The entering argument is that the Philippine Islands are a very challenging area for overhead surveillance. Recent operations in the Middle East may have made the task of gathering overhead imagery seem relatively easy. Nathan Hodge of Defense Week noted that:

At the start of Operation Enduring Freedom, the agency that collects satellite intelligence for the military raced to update its geospatial images of the region. But it had one key advantage: Afghanistan is a relatively sparse, open country that makes the task of capturing overhead pictures much easier.

The United States may not have that luxury in the next phase of its war on terror. The head of the National Imagery and Mapping Agency (NIMA), [now renamed as the National Geospatial Intelligence Agency], acknowledged that U.S. satellites and reconnaissance aircraft have a more difficult time operating over places like the Philippines, where clouds and dense jungle foliage obscure the ground. "The challenge posed in the Philippines is very different" from places like Afghanistan or Iraq, said retired Air Force Lt. Gen. James Clapper, the director of NIMA (NGA). "That's why you need other forms of sensors to compensate for that." [Hodge N, 2002]

2.4.1 Indo-Atmospheric Environment

The overall physical region is characterized by unpredictable environmental conditions due to multiple volcanic eruptions. The combination of volcanic activity, fires, and heavy rain can dramatically change the lands geography. The eruptions and associated fires may adversely impact visual surveillance and flight operations. The climate is tropical marine and heavy rain can be expected in all regions. The terrain is mostly mountainous with narrow to extensive low lying coastlands with 36,289 km (Philippines) of coastline. Approximately 15 cyclones are expected per year.

The sea surveillance environment is challenging and includes the extremes of both blue water and the littoral. Water depth ranges from shallow littoral areas to 10,540 meters in the Mindanao Trench.

The electromagnetic environment is characterized by interference from weather disturbances and high jamming from adversaries, particularly in the UHF spectrum.

2.4.2 Environmental Factors for Launch and Flight Operations

TacSat presents unique challenges in that the launch time must react to the needs of the tactical commander. It is assumed that TacSat must be available year round and that the environment around the launch site will be able to support year round operations. The environmental conditions for launch include temperate climate and a position along the equator (to reduce lift requirements). The ideal launch area also will have light winds and controllable acoustic, vibration, and shock levels. Since TacSat is not being launched from this region the evaluation of weather with respect to launch must be done from the planned launch site.

2.4.3 Environmental Factors for Sensor Performance

TacSats remote sensing objectives are quite different then those of typical commercial satellites. Commercial systems use full spectrum imagers to record variances in vegetation in one spectrum and perhaps measure cloud cover in another. Within the Philippine Sea scenario, TacSats imagery requirements are more limited and need to detect objects such as ships in ports, trucks in dense environments and/or detect movement of volcanic lava.

Atmospheric factors that affect sensor performance include absorption (atomic and molecular processes), scattering (aerosols-dust, fog, clouds, smoke) and turbulence (from temperature variations). Of these factors scattering due to aerosols is most unique to this scenario. Cloud cover and volcanic ash both act as aerosols and, as a result, may have an impact on sensor selection and performance. Although harder to quantify, the humidity resulting from the ocean (and moist ground) may also have an impact on sensor performance. In general, the environment limits the advantages of multi-spectral imagery and the primary imagery bands of interest are visible and far infrared.

2.4.4 Cloud Cover

The scenario itself presents several critical environmental problems. The Area of Operations has a high percentage of cloud cover and the mean cloud cover per day may exceed 60% in humid tropics. “It is practically impossible to get well-distributed cloud free images in tropical countries like the Philippines”. [Bussieres, Goita 1997] Data provided by Landsat shows that at least 50 percent cloud cover can be expected about 16 percent of the time, 30 percent cloud cover can be expected about 34 percent of the time, and at least some cloud cover (> 10 percent) can be expected about 73 percent of the time. [Pete M, Gardie J 1999]

The impact of significant cloud cover will affect the choice of imagery sensors for TacSat. As with aerosols, heavy cloud cover limits the advantages of multi-spectral imagers, as shown in Figure 2-1.

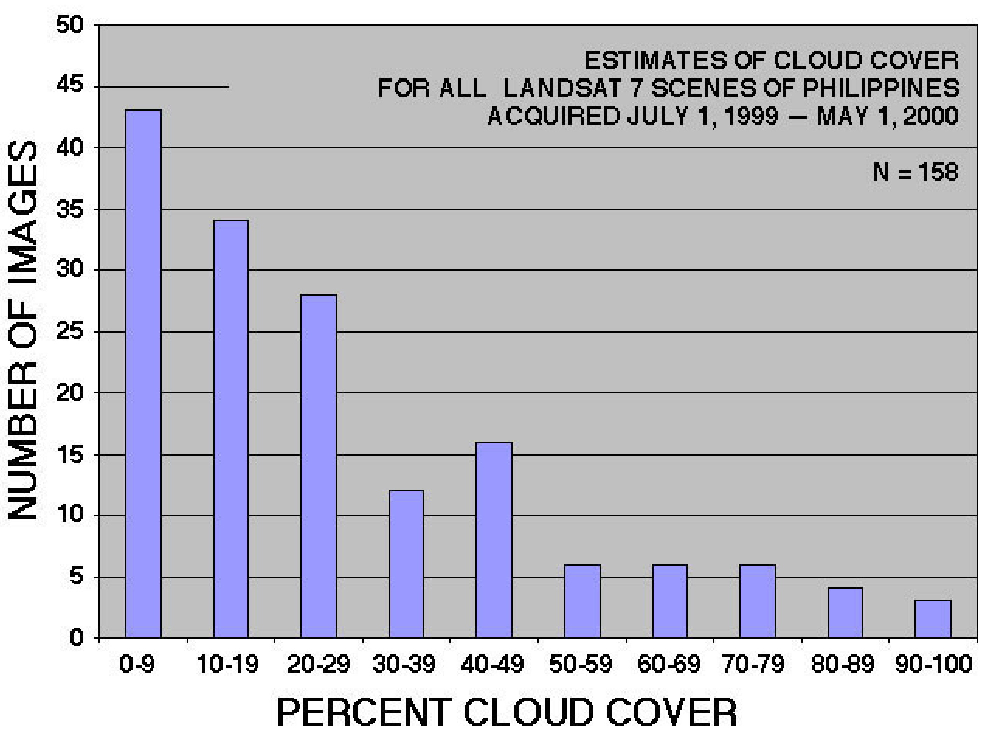

Figure 2-1. Cloud Cover [Pete M, Gardie J 1999]

2.4.5 Volcanic Dust (aerosol)

There are two volcanic plumes defined in the scenario which will impact sensor selection and performance. Volcanic ash can throw aerosols of small particulates up as far as the stratosphere, where they can persist for months or years. However, only if the concentration is very strong is there likely to be an effect on vertical or near-vertical viewing. The effect, when it occurs, is fairly broadband, though it appears to be greatest in the visible region. [Pease CB, 1991] Therefore, the impact of volcanic plumes in the region will drive sensor selection to the middle/far Infrared spectrum.

2.4.6 Jungle

The thick vegetation (jungle) environment provides serious challenges for remote sensing. Heavy vegetation has the capacity to block visual and most infrared imagery as well as communications downlink to the CDLS/MIST station.

2.4.7 Indo-Atmospheric Environmental Issues-Conclusion

The environmental challenges in this scenario are extreme and will limit the effectiveness of all imaging sensors. Although multi-spectral and hyper-spectral imagers can produce useful information these environmental conditions do restrict their performance and make it difficult to justify the associated complexity and cost. The most cost effective "tactical" sensors in this environment may be panchromatic (visual) and far infrared.

Heavy rain and cloud cover bolster the advantages of lower frequency communications such as UHF or S band over higher frequencies such as X, Ku, or Ka for general communications requirements.

Weather can diminish the performance and operation of the payloads of all host systems. However, of the systems considered in this study (commercial satellites, Global

Hawk, and TacSat); weather most adversely affects Global Hawk. Rain and clouds have no impact of satellite flight operations while they can severely restrict or eliminate Global Hawk flight operations.

2.4.8 Space Environment

The "space environment" is characterized by near vacuum, low gravitational acceleration, ionizing radiation, extreme thermal gradients, micrometeoroids, orbital debris and extreme variation in temperatures. One objective of TacSat design is to minimize the need for space hardening to reduce weight and ultimately cost. To this end understanding the space environment is critical in making design trades for both design and operation of the TacSat system. This section outlines a few of the most important space environmental factors directly related to the design principles of TacSat.

2.4.8.1 General Space Environmental Factors

LEO orbits experience near, but not total, vacuum which results in drag and orbit decay. The consequences of near (but not total) vacuum include the need for propulsion and the need to account for chemical reactions between the space atmosphere and spacecraft materials. As a minimum some type of non-oxidizing material will be required to account for the oxidizing effects of atomic oxygen. Electronic circuitry must be designed to account for unintended conductive paths (Paschen breakdown).

Micrometeoroid impacts to spacecraft are rare but they are more common in lower orbits due to the gravitational attraction of the earth. Though space debris is a continuing and increasing problem especially at low orbits, TacSat lifespan and low cost requirements may dictate that no special protection be engineered to protect against this threat. Some mitigation is inherent in choosing altitudes less than 550 km since the debris density seems to be worst at altitudes of 600-1000 km. [Griffin M.D, 2004] (Space debris below 550 km is subject to faster orbit decay and reentry into earth atmosphere)

In some cases LEO satellites require protection against space plasma which can cause "absolute charging". Absolute charging may in turn cause "sputtering" in which

large negative charges attract ions to impact and damage the surface of the spacecraft. Naturally occurring radiation impacts spacecraft at all altitudes but the impact is generally less for LEO then geostationary (GEO) type orbits. Shielding is less critical for spacecraft designed for short life (1-2 years). Shielding is also less effective for LEO satellite as heavier protons (not electrons) dominate LEO altitudes.

2.4.8.2 Radiation Factors

TacSat designers must consider the effects of the Van Allen Belts in both design and operation. The Van Allen radiation belts were first detected by the first U.S. satellite Explorer I, which was launched during the International Geophysical Year of 1957-58. They are composed of energetic charged particles trapped inside the Earth's magnetic field, which surrounds the Earth like a ring doughnut and vary according to solar activity. The location and composition of the belts are not universally agreed upon but they are generally thought to be composed of two belts (inner and outer) though some scientists have reported belts diverging and converging from 2 to 4 belts. They have also changed in composition over time.

Scientists have been trying to explain why the number of charged particles inside the belts varies so much. A major breakthrough came when two rare space storms were observed that occurred in October and November of 2003. During the storms part of the Van Allen radiation belt was drained of electrons and then formed much closer to the Earth in a region usually thought to be relatively safe for satellites. "When the radiation belts reformed they did not increase according to a long-held theory of particle acceleration. Instead, very low frequency radio waves caused the particle acceleration and intensified the belts”. [Dyer C, 2003]

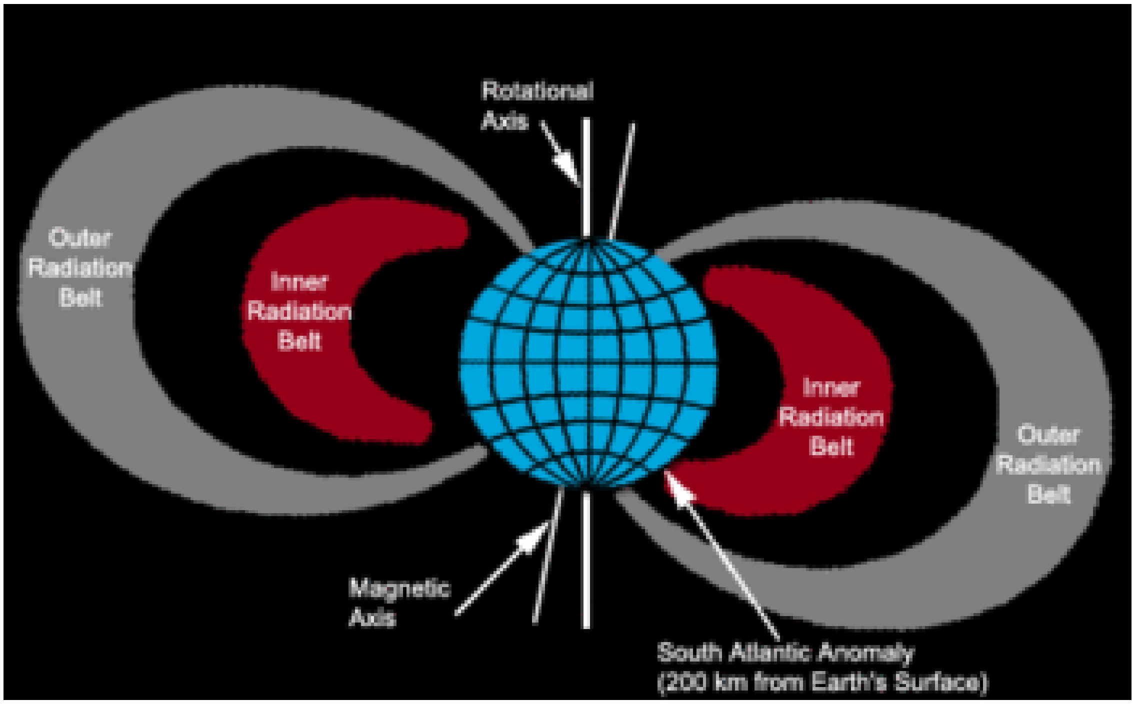

Figure 2-2. Van Allen Belts [*from Wikipedia*]

The outer belt extends between altitudes of about 10,000–65,000 km and has its greatest intensity between 14,500 and 19,000 km. Given these distances, the outer Van Allen Belt will not be a factor in TacSat design or operation.

The "inner" Van Allen Belt generally extends from about 900 km (~600 miles) to 4800 km (~3,000 miles) altitude. Importantly, the Inner Van Allen Belt dips down until it is only around 321 km (~200 miles) off the surface of the planet over the south Atlantic between about 35 and 60 degrees latitude. "This "anomaly" is a result of the displacement of the dipole term in the geomagnetic field away from the Earth's centre, there is a region in the South Atlantic where the trapped radiation mirrors lower altitudes. This is called the South Atlantic Anomaly (SAA) or Brazilian Anomaly and dominates the radiation received in LEO. In addition, highly inclined LEOs intersect the outer belt electrons at high latitudes in the so-called horn regions". (Figure 2-2) [Dyer C, 2003]

This inner belt contains high concentrations of energetic protons with energies exceeding 100 MeV, trapped by the strong (relative to the outer belts) magnetic fields in the region. "It is believed that protons of energies exceeding 50 MeV in the lower belts

at lower altitudes are the result of the beta decay of cosmic ray neutrons. The source of lower energy protons is believed to be proton diffusion due to changes in the magnetic field during geomagnetic storms.” This belt also contains electrons, low-energy protons, and oxygen atoms with energies of 1–100 keV. When these electrons strike the atmosphere they cause the polar aurora. [Tascione T.F., 1994]

Since the Van Allen belts themselves contain concentrations of charged particles, going through them presents its own hazard and that radiation can and has caused damage to spacecraft in LEO. Hubble orbits the Earth about every 97 minutes at an altitude of about 353 miles (569 kilometers) and inclined at about 51.60 degrees. It sometimes shuts down its electronics when riding through a high radiation zone (such as the Van Allen belts over the South Atlantic). Other space craft such as the Shuttle and the Space Station try to avoid radiation damage by staying out of the affected areas. The space station is located in orbit around the Earth at an altitude of approximately 360 km (220 miles). Shuttle orbits range from 290 km (for the heavy Columbia) to 360-390 km (space station altitude).

Radiation belts can become more intense as a result of naturally occurring solar storms or manmade nuclear explosions. When the sun acts up, the area outside the Van Allen belts becomes thick (i.e., high flux) with dangerous, high-energy charged particles. Lead author, Dr Richard Horne of the British Antarctic Survey (BAS) says "Solar storms can increase radiation in the Van Allen belts to levels that pose a threat to spacecraft.” In 1962 a high altitude nuclear burst caused the Van Allen belt radiation to be amplified and several satellites ceased operation.

<u>Spacecraft riding through the Van Allen belts during these events run a high risk of both short and long term damage</u>. Solar cells, integrated circuits, and sensors can all be damaged by radiation. Electronics on satellites must be hardened against radiation to operate reliably. Miniaturization and digitization of electronics and logic circuits have made satellites more vulnerable to radiation, as incoming ions may be as large as the circuit's charge. “An object satellite shielded by 3 mm of aluminum will receive about 2500 rem (25 Sv) per year”. [Ptak A, 1997] The effects of the Van Allen Belts were studied for their impact on the SDI Weapons Platforms. The conclusions were: “The

calculated results show that the SDI platform will survive long term (10 years) exposure to natural VAB protons and electrons. However, when the electron belts are enhanced by the detonation of a nuclear weapon, high levels of radiation can be expected in components mounted on or near the surface of the spacecraft. These dose levels are sufficient enough to produce damage in the most sensitive components." [Barnes JM, Santoro RT 1988]

2.4.9 Exo-atmospheric Environmental Conclusions

There are advantages in placing remote sensing devices in high altitude orbits (>600 km) and there is a trend to raise orbit altitudes for surveillance missions. The consequences are that natural radiation effects are more significant, particularly those resulting from trapped protons.

LtCol (ret) Edward B. Tomme writes in his paper "The Strategic Nature of the Tactical Satellite" that "The requirement for satellites in magic orbits (HEO) to regularly traverse the inner Van Allen belt will call for some mitigating engineering design to ensure that the one-year goal lifetime can be met. This mitigation can come in one of two ways: by using radiation-hardened, space-qualified components or by adding additional shielding to protect the cheaper commercial off-the-shelf electronics. The first method will almost certainly cause the budgetary goals of the program to be exceeded. The second method will add significant weight to the system. Neither solution seems palatable." [Tomme, E. 2006]

LtCol Tomme is probably correct regarding the requirement to add expensive space hardening to TacSat but the "magic HEO" orbit he alludes to may not be the best solution for TacSat. Avoiding challenging space environments can be accomplished by careful consideration of altitude and inclination. It is important to keep spacecraft out of challenging radiation environments such as Van Allen Belts. This is even truer for scenarios where nuclear weapons may be used. Equatorial orbits inclined below 30^0 and below ~600km will minimize the affect of radiation and collisions with micrometeoroids and other "space debris". An equatorial orbit (supporting this Philippine scenario) inclined at $<20^0$ will avoid the SAA though TacSat missions in general may have to

account for it if higher inclinations are required. In general, higher inclinations (about 30^0) may require orbits at lower altitudes to avoid radiation and the cost of engineering the system to compensate for it.

It appears that TacSat will incur significant benefit by remaining in orbits with altitudes and inclinations that avoid both Van Allen radiation belts and impact with space debris and micrometeoroids. These lower orbits will also help TacSat remain less susceptible to the harmful affects of nuclear air bursts. Optimal altitudes for satellites inclined at 20^0 may range from 350km to 600km.

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3.0 REQUIREMENTS

3.1 MISSION OBJECTIVES

This chapter establishes the mission objectives based on the Philippine Sea scenario described previously. It begins by establishing desired outcomes for the military and humanitarian operations and then describes some of the military operations required to achieve these. Space mission objectives are then derived from the military operations requirements. Specific performance parameters are then generated based on the space mission objectives required to meet the military operations.

3.1.1 Conduct humanitarian Operations

The volcanic eruption has caused widespread suffering and there is an urgent need to transport necessary supplies into the region. There is also a need to maintain local order and protect both the local population and the non-government organizations (NGO) trying to lend assistance.

3.1.2 Stabilize Local Government

In order to prevent the radical Islamists from seizing and maintaining control, the local government needs to be supported and stabilized. This involves providing security and establishing local order as well as insuring the local government has the communication and transportation resources to respond to the needs of its citizens.

3.1.3 Protect the Oil

It is important to insure the security of the oil facilities on the Spratly Islands. These are attractive targets for Indonesia as well as Islamic radicals seeking to destabilize the region. Loss or damage to these facilities could result in economic hardship both locally and globally.

3.2 MISSION REQUIREMENTS

The requirements below describe the military functions and the C4ISR support required to occur in order to support the Mission Objectives outlined above.

3.2.1 Establish a Recognized Situational Awareness Picture

The situation in the scenario is complex and changing rapidly. In order to meet the objectives outlined in the scenario with minimal risk and minimal application of force, it is critical that the situational awareness picture is established and maintained. Persistent imagery of activity on both land and sea is required to maintain situational awareness. Communication services are required to support persistent monitoring of distributed sensor fields.

3.2.2 Land and Support Forces Ashore

In order to meet the operational goals described above, forces will need to be landed and supported. These forces will facilitate transport of supplies, establish security and conduct operations against the rebels in the southern islands. Imagery and communications support is required to enable the tactical commander to monitor transportation corridors and maintain lines of communication throughout the AOR.

3.2.3 Coverage

For this scenario, imagery coverage and communications capability is required over widely dispersed Areas of Interest (AoIs) bounded roughly by 7°S and 20°N latitude and 105°E and 132°E longitude.

3.2.4 Suppress Rebels in the Southern Islands

The rebels in the southern islands pose a clear threat to local security and regional stability. Legitimate control must be established with minimal application of force.

Positions and movements of rebels in the Southern Islands must be frequently reported to the commander. Imagery support is required to enable the tactical commander to monitor rebel forces in the southern islands.

3.2.5 Suppress Indonesian Navy (ASUW)

The government of Indonesia may see it as in their interests to encourage the local rebellion. They have sortied their naval forces and it is important to keep these forces from exerting influence while avoiding direct conflict if possible. Imagery and ELINT support is required to track surface forces.

3.2.6 Suppress Kilo (ASW)

Perhaps the most serious naval threat from Indonesia is their Kilo class diesel electric submarines. Imagery and ELINT support is required to locate and track these and insure they do not get into a position where they may pose a threat to friendly forces.

3.3 PERFORMANCE REQUIREMENTS

The performance requirements can be developed by decomposing the mission functional requirements. Using the functional requirements and the Philippine Sea scenario performance requirements were derived to meet the mission needs. A detailed breakout of the performance requirements are shown in Table 3-1 and Table 3-2.

The modeling team used these performance requirements to develop the system requirements. Those requirements that could not be meet were discussed with the group and trade-offs were made to produce a feasible design. Although not specifically addressed as a requirement, system cost is a critical issue and is addressed in the gap analysis and section seven.

3.3.1 Coverage

This requirement supports the coverage of both ISR data and communications data over the entire AOR. The AOR can be defined as an irregular polygon within 7°S

and 20°N latitude and 105°E and 132°E longitude as depicted in Figure 5-1. In addition to the geographical coverage requirements, there is an additional requirement to sense in restricted airspace undetected by the enemy.

3.3.2 Capacity

Data transmission requirements exist for voice, tactical and ISR data. The TacSat must have the ability to transmit and route this data within the time allotted to provide the Combatant Commander reliable data in near real time. As the data capacity for voice is quite small the limiting factor for capacity is the telemetry link for imagery. To support the tactical commander in this scenario TacSat must be able to transmit all imagery data in the same pass overhead as it was recorded. While 1 to 2 Mbps is adequate for communications, imagery demands up to 274 Mbps.

3.3.3 Resolution

Resolution is a key driver in the development of the TacSat system. To provide tactical value to the warfighter imagery must have the ability to obtain the identity of many items both large and small such as vehicles, boats, and troop movements.

3.3.4 Interoperability

Interoperability can be defined as the systems ability to exchange data with other services, systems, units, or forces, and to use those services to operate effectively together. [Joint Pub 2001] Specific interoperability requirements for communications and imagery are highlighted in the performance requirements section.

3.3.5 Availability

The system payload must be available for tasking from the tactical or local joint task force commander at all times.

3.3.6 Launch Time

In order to be of use militarily, tight timelines must be maintained for the requesting and launching of the tactical space mission. The JTF commander should establish his requirements and communicate them to the tactical space mission operations node. The time from service request to the time the constellation is fully operational must be no less then 10 days.

3.3.7 Duration

The scenario requirement includes 60 days of high intensity operations, 60 to 360 days of medium intensity operations, and 60 to 360 days of international contingency operations. Therefore, the minimum duration required is 160 days while the maximum duration required is 780 days or just over two years. Two years was selected as the duration for the purposes of this study.

3.3.8 Requirements Summary

Table 3-1. Communications Requirements Summary

Performance Parameter	Threshold	Objective
Coverage	24 hrs per day 20^0N to 7^0S / 105^0E to 132^0E	24hrs per day 20^0N to 7^0S / 105^0E to 132^0E
Capacity	1- 1.0 Mbps secure data/voice channel	2- 1.0 Mbps secure data/voice channels
Interoperability	Combatant commander, JTF	Combattant commander, JTF, Allies, Coalition.
Availability	97% Constellation Availability 95% Link Availability	99% Constellation Availability 99% Link Availability
Launch Time	Within 10 days of launch order	Within 3 days of launch order
Duration	1 year	3 years

3.3.9 Surveillance Performance Requirements

Table 3-2. ISR Requirements Summary

Performance Parameter	Threshold	Objective
Coverage- (Temporal Resolution) for each AoI	Every 2 hours	Every 1 hour
Coverage- regions (LAT)	20^0 Deg N to 7^0 S	20^0 Deg N to 7^0 S
Coverage- regions (LONG)	105^0E to 132^0E	105^0E to 132^0E
Coverage- # of Areas	5 AoIs imaged every 1-2 hours; >1600 NM separation	8 AoIs imaged every 1-2 hours; > 1900 NM separation
Coverage-Restricted Airspace	No restrictions	No restrictions
Capacity (downlink)	108 Mbps secure channel	274 Mbps secure channel
Resolution-Spatial	2 m (panchromatic)	1 m (panchromatic) 4 m (IR)
Resolution- Spectral	Panchromatic	Panchromatic; Middle far IR
Interoperability	CDL/MIST/VMOC	CDL/MIST/VMOC
Availability- Constellation (system)	97%	99%
Availability- Link	95%	99%
Availability- Time to "on station" (days from request)	10	3
Availability -Duration (years)	1	3
Data Delivery time (from request to delivery to tactical user)	3 hours	1 hour

3.4 CONCEPT OF OPERATIONS (CONOPS)

System performance and operations planning must be consistent with needs and objectives of the war fighter. TacSat CONOPs must be in alignment with FORCEnet Functional Concepts for the 21st Century as approved by the Chief of Naval Operations (CNO) and the Commandant of the Marine Corps (CMC). Any data or service for the war fighter should be developed and provided with consideration of the war fighter’s perspective or view. When designing systems for employment, one must get inside the war fighter’s head, perspective or frame of reference. --- OODA Loop = Observe, Orient, Decide, Act. The OODA loop provides a fundamental basis for implementation of a

Command and Control Process. The ISR mission or service provides realization for the "Observe" and "Orient" phase of the OODA/Command and Control process and battlespace awareness.

Much of the Intelligence information will be "double posted" under the FORCEnet CONOPs. Collections nodes may post or provide time-sensitive data for immediate exploitation of users as appropriate. The same information may be picked up by an analysis activity and reposted as intelligence that has been processed, analyzed, evaluated and interpreted. [CNO-CMCMCDP 6/NDP6]

The objective is to optimize the flow of useful information while restricting the flow of unnecessary information. In support of this, all network nodes become providers and users of service on the network. Services are any work performed by one node for another. Decision makers can "pull" information as required while other information may be "pushed" as deemed important or a requirement by higher authority. This FORCEnet characteristic may support the Capstone TacSat "store and forward" concept with regard to some information sharing and dissemination.

3.4.1 TacSat Operation Considerations

Per Unified Command Plan 2002 (UCP 02), Space Forces assigned to the Air Force component to U.S. Strategic Command (USSTRATCOM) provide day-to-day global space support to unified commanders per SECDEF directed command and support relationships. TacSat force planning will be consistent with current AEF processes and functional area manager (FAM) guidance. Additionally, the necessary space supporting capabilities and personnel will be apportioned to UTCs and AEF cycles, and designated for use in coordinated OPLAN annexes. Finally, the air and space operations center (AOC) weapon system will provide the basis for operational C2, but will require capabilities upgrades in order to successfully accomplish assigned responsibilities. [Volz]

Figure 3-1 provides an Operational View (OV-1) of proposed TacSat CONOPS by the USAF. CONUS-based space operations are integrated (virtual and on station) in theater level planning and, when alerted, begin generation activities to provide on-demand support to theater. JWS forces, space systems (space, link and ground) and

space support (i.e., spacelift) are elevated to "alert" status to quickly respond to JFC tasking and demand (i.e., communications, ISR, etc.). Forces must be operational within 72 hours of call-up. When requested by the JFC, USSTRATCOM, as a supporting command, will direct the launch of TacSat assets through his Air Force Space component, which has global and expeditionary space forces assigned. When operational (in near-space or on orbit), the payload(s) will CHOP to theater and be dedicated to the needs of the JFC. AF mission operations may continue in a supporting relationship for satellite vehicle health & safety monitoring, anomaly resolution, collision avoidance, beyond line-of-site commanding, and end-of-life disposal operations. [Volz]

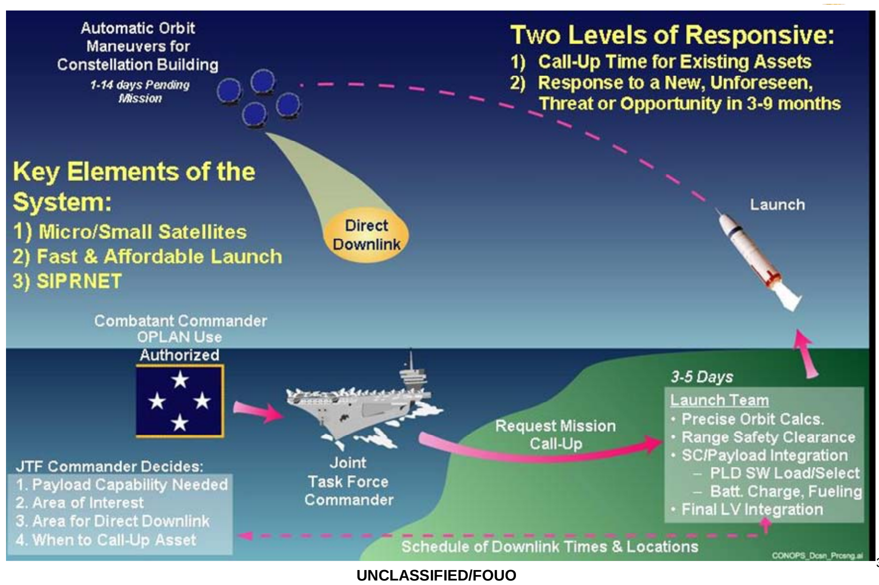

Figure 3-1. TacSat CONOPS [from ORS CONOPS]

3.4.2 Operations

Thirteen key functions are performed by Mission Operations:

Mission Planning; Activity Planning & Development; Mission Control; Data Transport/Delivery; Navigation & Orbit Control; Spacecraft Operations; Payload Operations; Data Processing; Mission Database Maintenance & Archiving; Systems Engineering, Integration & Testing; Computers & Communications Support; Software Development/Maintenance; Mission Operations Management. [Larson W, Wertz J 1999]

Hardware, software, people and procedures must operate together for completion of these key functions. Trade-offs between automation and ground crew operations must be considered with regard to operating and life cycle cost. [Larson W, Wertz J 1999]

Spacecraft operations include launch and ground control operations This CONOPS discusses the general operations of each of these as well as specific CONOPS for "tactical" operations such as collecting and down-linking high resolution imagery.

3.4.2.1 Launch Segment Operations

The launch segment for a space system is typically one of the most expensive and time-intensive parts of the overall system. Space programs plan and schedule launches well in advance. There is considerable infrastructure involved in integrating payloads to buses and moving the resulting spacecraft to the selected launch facility. Once at the launch facility there is considerable more effort and time involved in mating the spacecraft to the launch vehicle and transporting the resulting rocket to the launch pad. Countdowns then follow during which subsystems are monitored, checked and rechecked before the final go ahead is given for launch.

In order to have military utility TacSat must be launched in timelines that are not supported by this type of process. It will be necessary that ground infrastructure and inventories be placed at the launch location(s) that will support TacSat launches. Candidate locations are Kennedy Space Center, Vandenberg Air Force Base, and of particular importance to the scenario, Kwajelein atoll. This infrastructure would need to include warehousing for payloads and buses. In addition the launch vehicles themselves would need to be pre-positioned and stored at the launch site. This poses challenges regarding the shelf life of these items. Launch vehicles typically have a shelf life of three years. [Brown C, 2002] This challenge coupled with the U.S. military philosophy that "we train as we fight" leads to the conclusion that TacSat launches will need to take place regularly. This will have the added benefit of increasing the numbers of payloads, buses, and launch vehicles produced and thus driving down unit costs.

Another logistical challenge associated with the pre-staging of launch vehicles involves the sizing of the thrust required. Typically a launch vehicle is chosen based on

the desired orbit and expected general size the spacecraft. The launch vehicle is then selected. When finished there is typically still some variation between the velocity the spacecraft needs to attain the desired orbit and the velocity the launch vehicle will provide for the spacecraft based on its final mass. Liquid fueled rockets shut down by inhibiting the flow of fuel when the desired velocity is attained. Liquid fueled rockets however, introduce logistical requirements in terms of handling and storage of their volatile fuels. Solid rocket motors can tailor their delivered velocity to some degree by what is known as their “off load” capability. Essentially the solid rocket motor case is poured so the maximum impulse, (and the resultant velocity), delivered is tailored to the spacecraft being carried into orbit. [Brown C, 2002] In the TacSat pre-stage scenario, there will be variations in total mass from one mission to the next. There will also be variation in the exact orbits selected from one mission to the next. The timelines required for an operationally responsive tactical capability does not allow for custom pouring of launch vehicles. There are two possible concepts that may provide solutions. First, a family of launch vehicles tailored to the various bus and payload combinations could be pre- staged at the launch facilities. Second, the variation in mass could be handled by using launch vehicles that are sized for the worst case combination of bus, payload, and orbit. For combinations that require less total impulse the difference could be made up by adding ballast to the system.

3.4.2.2 Ground Control Operations

Ground operations consist of three functions. The first is payload operations, the second is spacecraft operations, and the third is mission operations.

The Consolidated Space Operations Center (CSOC) is the probable central locations for TacSat control. They will provide tracking, control altitude, monitor health via telemetry, and provide orbit maintenance functions. No special ground control infrastructure is planned for TacSat. The existing ground station services, Air Force Satellite Control Network, will be used in order to save on costs. This network has nodes in New Hampshire, California, Hawaii, Guam, Diego Garcia, Greenland, and England and is interconnected by robust satellite and terrestrial communications networks. They communicate to the spacecraft using the S-Band Space Ground Link Subsystem SGLS.

[Larson W, Wertz J 1999] The MCC and SOCC at one of these existing nodes or another Air Force location will provide robust links to the AFSC such as Vandenberg or Falcon Air Force Base in Colorado.

3.4.2.2.1 Payload Operations

In order for TacSat to achieve its full military utility for a tactical user the payload operations need to be carried out in a distributed fashion. This is the concept that underlies the Virtual Mission Operations Center (VMOC) concept. Using a simple, intuitive graphical user interface and standard TCP/IP communications; the VMOC provides a tool that allows distributed users to task the payload. This requires considerable capability within the VMOC software and supporting communications. The software must have accurate telemetry and tracking data from each satellite in the constellation and the ability to project orbits forward so that specific targets can be scheduled by the users. In addition there needs to be mechanisms to deal with contentions between different tactical users. Much like the current national systems TacSat will rapidly become a system with more tasking then it can completely accommodate. Careful and efficient scheduling of tasks will be critical. This can be particularly challenging in a distributed environment. Experiments have already been conducted with this approach in an experiment where a CISCO router aboard a spacecraft was remotely controlled using VMOCs.

3.4.2.2.2 Spacecraft Operations

Although the proposed bus simplifies spacecraft operations as much as possible by maximizing automation, especially for guidance and navigation, there will still be a requirement to monitor telemetry and up-link commands to the satellite. The TacSat spacecraft operations mission will be assigned to the existing Air Force Satellite Control Network (AFSCN) for satellite control and maintenance in order to keep the costs associated with spacecraft operations minimal. While there will be additional cost both in terms of personnel and physical infrastructure such as consoles; this approach should still yield significant savings over building dedicated spacecraft operations centers.

3.4.2.2.3 Mission Control Center Operations

The task of the Mission Control Center (MCC) is to coordinate the needs of the payload operations and spacecraft operations. Tasking and commands are arbitrated between the two to insure the health and status of the spacecraft are maintained with minimum impact to the payload operations and vice versa. The mission control console and staffing should be co-located with the spacecraft operations control center (SOCC).

3.4.2.2.4 Tactical Operations

For TacSat, Tactical Mission Operations include control of the imagery, ELINT, and communication payloads. The Virtual Mission Operations Center (VMOC) is currently under development by the U.S. Air Force. This system, if it performs as advertised, will enable the tactical user to effectively manage TacSat payloads. This system, in the ACTD stages, provides space-based network-centric operations via Internet protocol (IP). The tactical commander will have direct control over satellite payload operations.

Tactical commanders will use computers terminals to pull down data from satellites or, if the desired data isn't readily available, the VMOC will schedule the satellite to collect the image. The VMOC provides a graphical user interface that enables the tactical users to view and control satellite and payload control status and history information. The software-based technology treats space and air assets like Internet addresses, permitting remote users to request information from them or to monitor the status of platforms.

A fallback alternative is for the tactical user to send requests for payload management directly to the AFSCN where staff can manage the spacecraft payload.

3.4.2.2.5 Tactical Imagery Operations

TacSat imagery downlink demands high data rates and will be managed by a Modularized Interoperable Surface Terminal/Common Data Link (MIST/CDL) in theater. This system, co-located with a tactical command center, will receive X-band data at up to 274 Mbps. Imagery analysts stationed at the command center will process,

evaluate, and disseminate imagery in accordance with the tactical commander's instructions. Once CDL has the images they are processed and salient data sent to tactical commanders via FORCEnet. (Figure 3-2)

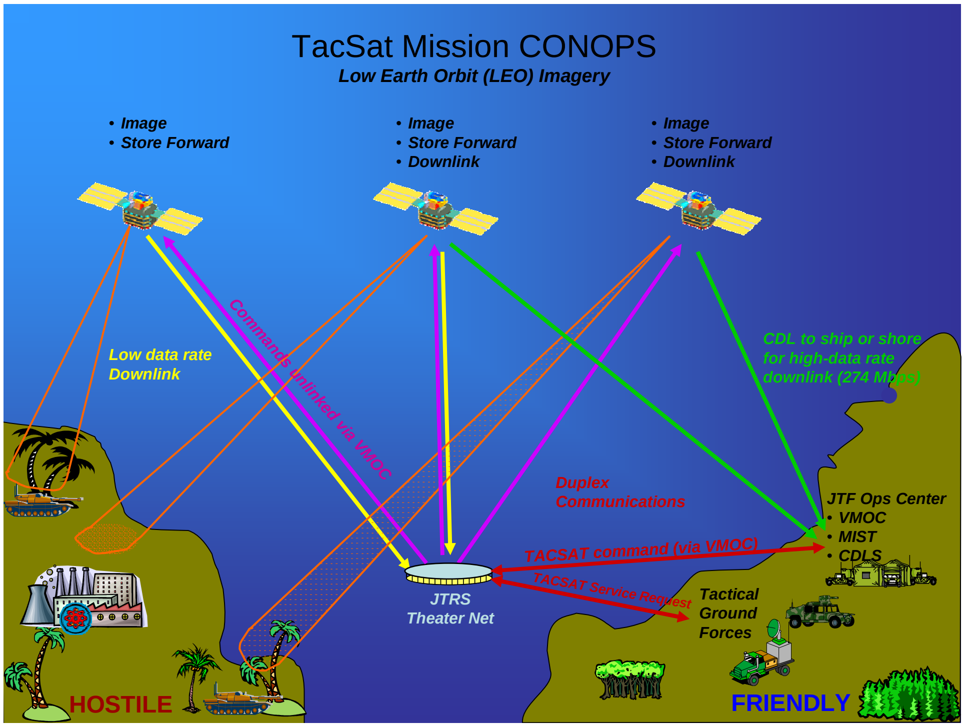

Figure 3-2. Imagery CONOPS

Alternatives to direct downlink include networks of connected ground stations for tracking and telemetry and to uplink commands to the satellite. NASA's "Tracking and Data Relay Satellite" (TDRS) is an alternative path that could be used to remove the constraint that payload data could only be downloaded while the satellite was overhead in the theater. The data could be transmitted to one of the geosynchronous TDRS satellites and then down linked to the earth. Once received at the TDRS ground station the data would be forwarded over standard DoD communications channels.

3.4.3 Sequence of Events (example):

1) Mission Request - The need service shall originate from the Joint Taskforce Commander or Joint Force Commander (JFC). This request may be

communicated per Numbered Fleet Commanders Operation Order (OPORD) directions, promulgation via Operational Tasking (OPTASK), Air Tasking Orders (ATO) or via Commander's Daily Intent; Task Force Commanders or JFC shall notify the respective Unified Combatant Commander of their intent. The JFC shall determine/synthesize the Mission requirement in 6 hours and submit to USSTRATCOM

2) Asset Assignment – The asset identification and assignment shall occur at USSTRATCOM.

3) Asset Prep & Launch – Asset assignment will assist or determine in identification of the launch location. Options consist of: Vandenberg AFB; Kwajalein Atoll; Wallops Island; NASA. Assets will be located in adjacent to launch sites.

4) Launch schedule- Launch schedule will enable full constellation to be on station in 3-10 days of JFC requirements determination.

5) JFC/Combatant Commander Control – Once the asset has achieved orbit and completed systems checkout, The Combatant Commander shall take Operational Control of the payload via SIPRNET.

6) Service/Product Retrieval – Data retrieval or communications reception shall occur at designated ground stations, Command ship or C2 node.

7) Analysis – Initial analysis shall occur in theater. Naval afloat platforms may use Fleet Intelligence Support Teams (FIST) if embarked; Follow-up detailed analysis may occur at designated service Intelligence agencies. The Intelligence agency shall actionable Intelligence to the JFC. This shall consider the exploitation of SIGINT and furnishing of Black & white photos/imagery.

8) Action – The JFC shall task combat assets for subsequent action in support of the mission execution/completion. The JFC shall review his/her prioritized task list for consideration of future tasking or re-tasking.

9) JFC reports mission complete to Unified Combatant Commander, Service Space operations and STRATCOM.

10) STRATCOM notifies the Operations centers when asset is to be placed back in inventory for re-tasking or end of life termination & re-entry.

3.5 CONSTRAINTS AND ASSUMPTIONS

Constraints include physical limits of systems and limitations on procurement options. Constraints can become mission drivers, that is, they drive the system complexity and cost and ultimately bound its effectiveness. Assumptions address operational issues such as availability of supporting systems.

3.5.1 Commercial-off-the-shelf (COTS) and Government–off-the-shelf (GOTS)

Selection of options for TacSat payloads, such as imagers and telemetry, will be constrained to COTS/GOTS whenever possible.

3.5.2 Launch Vehicles

Launch vehicles under consideration are constrained to existing low cost launch vehicles which include Falcon 1 ands Pegasus.

3.5.3 Space Resource Competition

Operations in other regions compete for overhead commercial resources and national resources for both communications and ISR. Support from national systems is assumed to be negligible and as such will not be considered in this study.

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4.0 ALTERNATIVES AND GAP ANALYSIS

4.1 DESCRIPTION OF ALTERNATIVES

This section identifies current systems that may meet mission requirements. It includes a brief discussion of capabilities and limitations of both military and commercial systems. It examines existing systems such as commercial satellites and UAVs but does not include examination of alternative future concepts such as high altitude airships.

4.1.1 National Systems

National systems information is primarily classified and cannot be addressed in this study. One of the assumptions for this study is that these national systems are not available full-time due to tasking in other regions or due to intentional damage by hostile forces.

4.1.2 Commercial Sensors

Commercial sensors include various types of imaging and communications platforms. This section provides a representative list of available alternatives. It includes salient points of spectral, temporal, and spatial resolution as well as general information on orbits. Spectral resolution, the measure of its power to resolve features in the electromagnetic spectrum, is discussed in reference to the requirement to provide surveillance of various types of targets. Temporal resolution, or the revisit time, is discussed in reference to the requirements to revisit specific areas every one to two hours. Spatial resolution, or the level of detail in an image that is discernable, is discussed in reference to the requirement to provide one meter spectral resolution. (Table 4-1)

- EROS A is an Israeli imaging satellite that orbits at 480 km and provides 1.8 meter imagery resolution with a temporal resolution of 2-4 days.
- IKONOS orbits at 680 km and can obtain an 11 km swath of data at 1-meter resolution. Imagery is collected at 11 bits per pixel and compressed to 2.6 bits per

pixel before transmission. Orbit time is 98 minutes and the revisit time for 1 meter resolution is 2.9 days. [Leachtenauer J, Driggers R 2001 p. 47]

- IRS-P3 is an India remote sensing satellite in an 817 km orbit with a temporal resolution of about 5 days. It images a swath width of about 200 km [Sarabhai V, 2006]
- IRS-P5/6/7 These advanced Indian imagers have a 2.5 meter resolution and a temporal resolution of 5 days. [Roy PS, Agarwal V 2006] They carry up to three cameras that operate in multi-spectral modes.
- LANDSAT orbits at 705 km with a temporal resolution of about 8 days. It can produce 100 images per day with a 24 hours turn around time. [Leachtenauer J, Driggers R 2001 p. 46]
- Orbview-3 provides 1 meter resolution panchromatic imagery and 4 meter multi-spectral with an 8 km swath width. It orbits at 470 km, inclined at 97 degrees and has a temporal resolution of about 3 days.
- Orbview-5 orbits at 660 km while collecting 0.41 meter resolution panchromatic mode and 1.67 meter multi-spectral mode imagery. When combined with Orbview -3 it will be able to collect 1.2 million square miles of imagery per day with a combined revisit rate of 1.5 days. [Andrews L, 2005]
- Quickbird orbits at 450 km, has a 93.5 minute orbit, and a temporal resolution of 3-7 days at nadir (depending on latitude). It boasts a panchromatic resolution of about 60 cm at nadir and multi-spectral 2-4 meter at nadir.
- SPOT (1-5) are a French constellation of 3 types of satellites orbiting at about 830 km and inclined at 98 degrees. They can provide 2.5 (Spot 5) - 20 (Spot 1-3) meters spatial resolutions. At the equator a single satellite (with oblique viewing) provides a temporal resolution of about 3 days. While the combined constellation has a temporal resolution of about 24 hours.

Table 4-1. High Resolution Satellites

Commercial Satellite Summary							
Sensor	Resolution Visible (m)	Resolution IR	Swath (km)	Temporal Resolution (days)	Orbit Altitude (km)	Orbit Inclination (degrees)	Downlink (Mbps)
EROS	1.5	na	13	4	480	99	
IKONOS	0.82	3.2	11.3	3	680	99	150
IRS P-3	188	n a	770	5	817	99	
IRS P-5	2.5	na	27-30	5	618	98	105
IRS P-6	2.5	24	1400	5	821	99	
LANDSAT (1-3)	40	75	185	8	705	98	15
LANDSAT 7	15	30-60	185	16	705	98	150
QuickBird	0.4	3.3	22	3 to 7	450	98	320
Orbview-3	1	4	8	3	470	97	2
Orbview 5	0.41	1.67	8	3	660	98	50
SPOT (1-5)	2.5-20	10 to 20	120-600	1 to 3	830	98	150
TOPSAT	2.8	5.7	25	4	600	98	

The commercial satellite systems currently incorporated into the military SATCOM architecture have several limitations of importance to military planners. These include

- General lack of protective features (*communications satellites*)
  - anti-jam (AJ)
  - anti-scintillation (AS)
  - low probability of intercept (LPI)/low probability of detection (LPD)
- Regulatory impediments to their use in foreign countries (Imaging satellites)
- Time to access, downlink, and process imagery (Imaging satellites)

Commercial imaging satellites generally do not employ the stringent techniques required for protection against deliberate disruption and exploitation.

The use of commercial systems is regulated in every country and as a minimum access to these sensors will take time to work out special operating agreements and site licenses. The commercial service providers generally pre-negotiate these agreements with the regulatory agencies of each country. However, the specific agreements and the restrictions placed on their use may vary widely from country to country. In many cases the satellite will already be under contract and not available. “While operating over

international waters and airspace, the Navy will not be restricted in their use, but shore-based units and units operating in the littoral may be affected by regulatory restraints imposed by the host nation". [Exec Sum]

Many commercial systems have adequate resolution to support these mission requirements but they have serious shortcomings. Their low rate temporal resolution, long lead time in down linking data, and uncertainty of availability due to political sensitivity and commercial competition make them non-viable alternatives for the tactical user. In addition, the feasibility of rapidly integrating them in the "FORCEnet" grid is uncertain.

4.1.2.1 Global Hawk Unmanned Aerial Vehicle

Global Hawk Unmanned Aerial Vehicle flies at ~340 knots and up to 65,000 feet with a range of about 13,500 miles or about 32 to 40 hours endurance. Its payload includes EO, IR, and SAR. The EO payload is a sensor with a 0.4 µm- 0.8 µm response. The IR payload is a MWIR sensor with a 3.6 – 5.0 µm bandwidth. The wide area search can cover 40,000 square miles in one day while the spot mode can collect about 1900 2x2 km frames per day. [Leachtenauer J, Driggers R 2001]

4.1.2.2 Surveillance Requirements

Table 4-2 details the distances between (example) areas that require surveillance for this scenario. (*For this study it is assumed there is one launch recovery site near Subic Bay).* Table 4-2 shows the distance required if one aircraft were required to survey all areas several times per day as per mission requirements (about 7697 km or 4782 miles). Table 4-3 shows it would take one Global Hawk ~13 hours (plus any loiter time) to complete one cycle it seems clear that one Global Hawk could not meet the requirement to surveil each area once every 1-2 hours. There are many surveillance plan options but in order to provide imagery every 1 (objective requirement) to 2 (threshold requirement) hours the Global Hawk would need to be within approximately 600 to 1200 kilometers on each AoI at all times.(*based on cruise sped of ~600 km/h plus 15 minutes loiter*) Four Global Hawks could meet the threshold requirement (every 2 hours) if one each were assigned as follows: 1) Volcano 1 and Volcano 2 sites, 2) Mindanao and East

Approach, 3) Surbaya and Jakarta, and 4) West Approach and Spratly Islands. Even this assumes that the Global Hawk is continuously on station and does not include and downtime of aircraft or ground station. It seems clear that providing imagery for areas geographically dispersed can seriously stress the capabilities of Global Hawk and that meeting the objective requirement of this scenario would demand numbers of Global Hawks that might be impractical.

Table 4-2. Distance between surveillance areas (KM)

Approximate Distance between Operational Areas (KM)									
	Subic Bay	**Volcano 1**	**Volcano 2**	**Mindanao**	**Spratly**	**W. Approach**	**E. Approach**	**Surbaya**	**Jakarta**
Subic Bay	0	297	112	919	450	1700	1400	2450	2600
Volcano 1	297	0	200	1100	770	1850	1700	2700	2830
Volcano 2	112	200	0	850	670	1800	1490	2550	2750
Mindanao	919	1100	850	0	800	800	1600	2000	2400
Spratly	450	770	670	800	0	1100	1150	2000	2100
W. Approach	1700	1850	1800	800	1100	0	1000	1050	1050
E. Approach	1400	1700	1490	1600	1150	1000	0	1600	1100
Surbaya	2450	2700	2550	2000	2000	1050	1600	0	550
Jakarta	2600	2830	2750	2400	2100	1050	1100	550	0

Table 4-3. Single Aircraft Mission Distance (KM/Miles)

Subic Bay	**Volcano 1**	**Volcano 2**	**Mindanao**	**E. Approach**	**Surbaya**	**Jakarta**	**W. Approach**	**Spratly**	**Subic Bay**	**Total KM**	**Total Miles**
0	297	200	850	1600	1600	550	1050	1100	450	**7697**	**4782**

4.1.2.3 Cost/Availability

The Global Hawk and its associated sensors have been upgraded several times increasing capability and cost. Reliability has been a serious issue with respect to both sensor operation and aircraft survivability. During Operation Enduring Freedom 2 of the 7 Global Hawks used were lost and there were numerous equipment failures.

The cost of Global Hawk includes the aircraft, mission control elements, launch recovery elements, segment support elements, and initial spares. Some contractor sites unrealistically report the cost of Global Hawk as low as 10 to 26 million per copy. [RQ-4 Global Hawk] In 2004 the GAO reported unit cost at about 123.2 million, while in 2006 the Air Force reported cost is about 145 million per copy. [GAO-05-6], [Justifying Sharp, 2006] Accurate operating “costs per hour” for Global Hawk are not available but would

include both aircraft and ground system operation. Ground crews would be needed for the duration of the deployment and not just during actual flight operations time. Rough costs for comparison would include three Global Hawks at $125M each ($375M total), plus operating costs, plus one assumed loss. Global Hawk requires either 3 C-141s or 2 C-17s to get equipment in theater. *Detailed cost analysis is contained in section 6 of this document.*

4.1.2.4 Summary

The Global Hawk can provide superior tactical reconnaissance under controlled conditions. It can provide long dwell time over any one target area and can host a variety of sophisticated sensors. It will meet or exceed both spatial resolution and spectral resolution requirements as well as provide other sensors capabilities (SAR/ELINT etc). However, it has serious limitations in this environment where targets are thousands of miles apart but still need surveillance updates several times per day. Maintaining temporal resolution requirements over the widely dispersed area would require several very expensive Global Hawks and their associated ground crews, landing areas etc. Additionally, it is likely that Global Hawk will not get permission to fly through Indonesian airspace and will not be able to survey ports in Indonesia. Its low altitude (compared to satellites) will result in additional communication relay requirements (i.e. getting data from Global Hawk flying over Indonesia requires a relay to get to a ground station in the Philippines).

4.2 GAP ANALYSIS

The purpose of this “Gap analysis” is to map the gap which exits between implied & specified mission requirements and the capability of existing systems. It includes, in addition, significant operational issues to consider as a result of choosing an alternative. The issue of national sensors is a “gray” area in that the availability is assumed to be reduced but it is not realistic to assume they are not available at all. National sensor capabilities are not included to avoid discussion of classified systems. Gaps are the inability of current systems to meet mission, functionality, and usability requirements. Specifically, this analysis will evaluate mission requirements against the capability of

existing systems such as commercial satellites and Global Hawk (GH). Performance of existing systems will be evaluated with respect to mission requirements at both the threshold and objective levels. Lastly, the potential for the TacSat system to mitigate these capability gaps will be addressed.

Applicable throughout this gap analysis is the constraint that national systems are not fully available due to other tasking such as support Middle East conflicts or due to damage from space environment or deliberate attacks from hostile forces. Similarly, the capabilities of commercial systems (CS) must be balanced against their constraints. Table 4-4 summarizes ISR requirements, current capabilities, and potential gaps.

Table 4-4. Gap Analysis

ISR and Communications Gap Analysis				
Performance Parameter	**Threshold**	**Objective**	**Capabilities Commercial System (CS) Global Hawk (GH)**	**Gaps-Mitigation**
Coverage- (Temporal Resolution) for each AoI	Every 2 hours	Every hour	GH can meet requirement if a dedicated unit is provided for each AoI. CS cannot meet requirement	3-4 GHs or 2 TacSats can meet requirements
Coverage- regions (LAT)	20^0 N to 7^0 S	20^0 N to 7^0 S	All	No capability gap
Coverage- regions (LONG)	105^0 E to 132^0 E	105^0 E to 132^0 E	All	No capability gap
Coverage- # of Areas	5 AoIs 1-2 hours; up to 1600 NM separation	8 AoIs 1-2 hours; up to 1900 NM separation	CS can meet requirement. GH can only meet requirement if a dedicated unit is provided for each AoI.	3-5 GHs or 2-3 TacSats can meet requirement
Coverage- Restricted Airspace	No restrictions	No restrictions	CS are restricted by treaty. GH requires long range oblique scanning.	TacSat can meet requirement
ISR Downlink Capacity (In theater)	108 Mbps over secure channel	274 Mbps over secure channel	Only GH can meet requirement (via CDL/MIST)	Potential gap. TacSat or GH, can meet requirement vis CDL
Command Control	Tactical Command Center	Tactical Field CDRs	GH can link to tactical command centers. Current systems do not support control by field CDRs	TacSat payload controlled by VMOC can meet requirement
Resolution- Spatial	2 m panchromatic	1 m panchromatic	All systems have this capability.	No capability gap
Resolution- Spectral	panchromatic	panchromatic; middle far IR	All systems have this capability.	No capability gap
Interoperability	CDL/MIST/ VMOC	CDL/MIST/ VMOC	GH are interoperable. CS do not meet requirement	No capability gap
Availability- System	97%	99%	All	No capability gap
Availability- Link	95%	99%	All	No capability gap
Access and Control (from theater)	< 15 minutes	< 5 minutes	Only GH can meet requirement	No capability gap
Data Delivery time (from request to delivery)	4.5 hours	1 hour	GH can meet requirement	No capability gap
Capacity	1- 1.0 Mbps secure Data/Voice channel	2- 1.0 Mbps secure Data/Voice channels	If available, CS have this capability.	Potential gap TacSat can meet requirement

ISR and Communications Gap Analysis				
Performance Parameter	**Threshold**	**Objective**	**Capabilities Commercial System (CS) Global Hawk (GH)**	**Gaps-Mitigation**
Planning & Logistics				
Duration (years)	1	3	CS can provide this capability	No capability gap
Availability (Launch or service request time)	Within 10 days of service request	Within 3 days of service request	CS require long lead time for contracts. GH requires ground station transport, runway arrangements etc	No capability gap
Cost-Theater Lift Impact	1 C-17	None	CS may provide this capability. Multiple GH demand excessive lift	TacSat can mitigate as it has no in theater lift requirements
Cost-In Theater staff support for ground ops (not payload)	<12	<6	CS meet this requirement. GH demands excessive support for ground operations.	TacSat can mitigate as it has no in theater staff requirements for ground ops

4.2.1 Coverage (Temporal Resolution)

Temporal resolution is defined as the frequency at which images are recorded or captured in a specific place on the earth. The more frequently it is captured, the better or finer the temporal resolution is said to be. Mission requirements specify a threshold requirement of 4 hours and an objective requirement of 1 hour for each of the areas of interest. The ability of various sensors to meet a temporal resolution standard depends on both on the physical capability of the system and the willingness (or ability) of the system owner to deploy the asset. National sensors capability is classified but any spaced based system has the physical capability to meet both threshold and objective requirements. However, as previously stated, this study assumes that national sensors availability is limited and cannot meet the temporal resolution requirements. Commercial remote sensing satellites are all in orbits designed for full earth coverage and as a result they have particularly poor temporal resolution near the equator. There are no commercial satellites that can physically meet threshold temporal requirements for this scenario. Global Hawk boasts long dwell time over any one area of interest but a single Global Hawk cannot meet temporal resolution requirements at the widely dispersed areas of interest. It might take 4 Global Hawks to meet requirements over the stipulated areas of interest. This does not include attrition and assumes continuous availability. This assumes 3 are flying near continuously and 1 spare is available (provided to account for historical attrition).

In conclusion, only Global Hawk can provide the temporal resolution required but it would take at least 4 to accomplish the task. TacSat can meet this temporal resolution given an unlimited constellation. The TacSat System Analysis section will address the ability of the TacSat system to meet these requirements.

4.2.2 Coverage Regions (LAT/LONG)

All potential systems can meet and exceed the requirements to provide surveillance for the equatorial region specified for this scenario.

4.2.3 Coverage (Number of Areas)

This scenario demands simultaneous coverage of several widely dispersed areas. Both national and commercial sensors have the capacity to provide reconnaissance over any targets within their field of view. Given the distance between targets (900-1900 miles) Global Hawk requires deployment of unique units to each AOR. TacSat has the same capability and same restriction as commercial sensors with respect to this requirement.

4.2.4 Coverage- Restricted Airspace

This scenario requires coverage of Indonesian Navy Ports and other restricted regions. Airspace will be controlled by Indonesia, Malaysia, and the Philippines. Indonesia usually denies airspace privileges to the U.S and even denied airspace over flight during tsunami operations. [Loy H, 2005] Given this history the fact that Indonesia is a hostile force in this scenario it is assumed that no over-flight will be allowed. Commercial satellites cannot as they are usually restricted by treaty for this type of surveillance. Global Hawk would be denied over-flight permissions and even oblique viewing would not allow surveillance of subject Navy ports. At 65,000 feet it would need to stay about 125 miles from restricted areas. TacSat has this capability and is a feasible alternative to mitigate this gap.

4.2.5 ISR Downlink Capacity

In order to be “tactical” images need to be quickly down-linked and forwarded to the tactical user. The capability of national sensors is classified. Commercial satellites generally downlink at ranges up to about 150 Mbps while Quickbird (as the name implies) downlinks up to 320 Mbps. Global Hawk can downlink via CDL and has other downlink modes as well. The TacSat system would have to meet threshold values to be “tactical”.

4.2.6 Command Control

The requirement to get data to the tactical user is critical so this requirement specifies the ability of the system to downlink and or forward data to the tactical commander. Clearly national sensors have the ability though the willingness (or unwillingness) to do this was the genesis of the TacSat program. Typical tactical ground stations do not have tracking or terminals for commercial remote sensing satellites. Routing (indirectly) data from commercial satellites to tactical command centers is feasible but would normally be routed at high speed to a ground station and then to the command center via WEB or other communications satellites (with lower data rates). It also means that potentially sensitive data exists and is controlled by the owner of the commercial terminal. In any case once the data is received at the ground station it is subject to the constraints of other communication systems.

Global Hawk can link directly with tactical ground stations via numerous means (Figure 4-1) but those systems themselves add constraints. First, they must be available, not tasked by other users and second, they must operate at data rates that support Global Hawk. Links other than direct CDL imply low data rates and non-tactical employment.

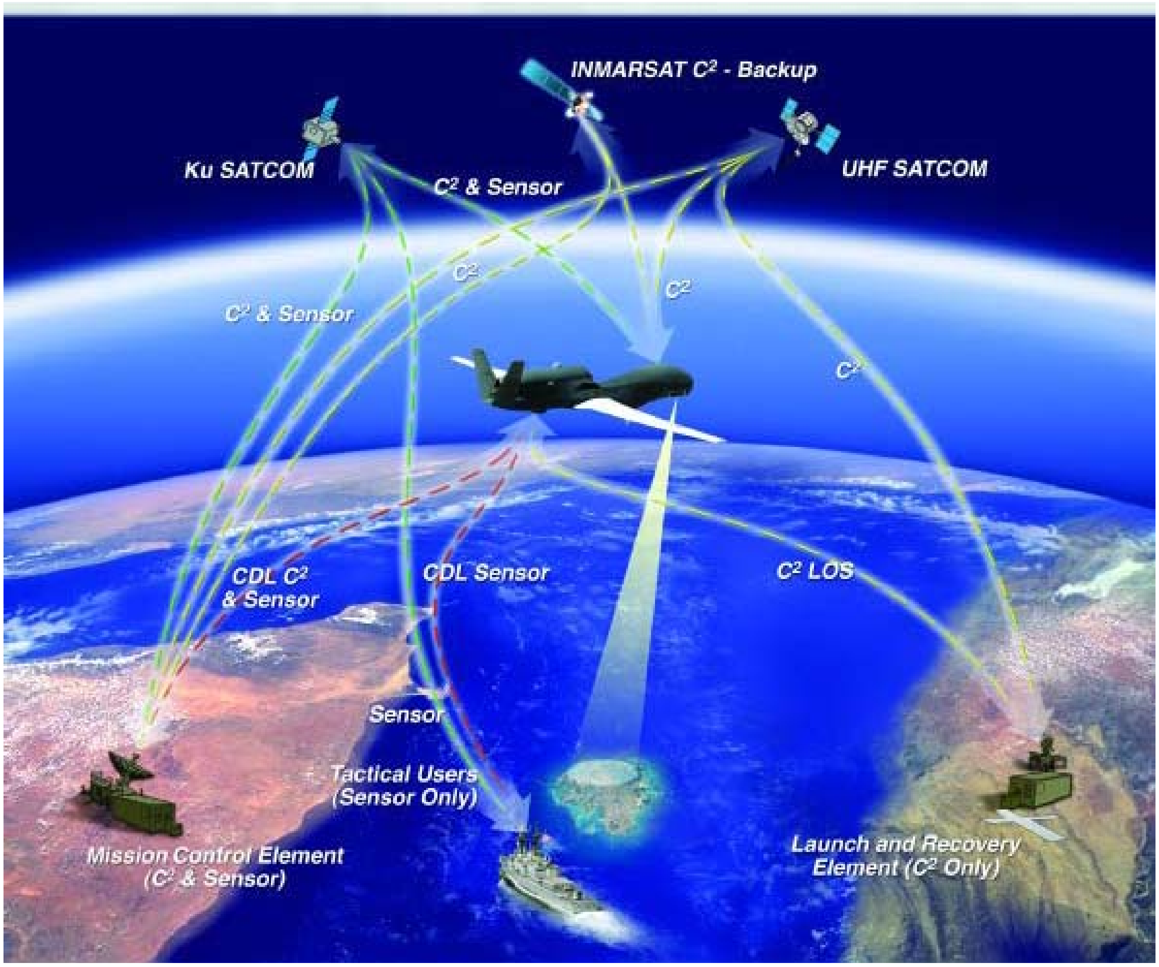

Figure 4-1. Global Hawk [USAF Graphic]

TacSat would need to directly interface with CDL/MIST ground stations and support associated high data rates. *Other relay type links (TDRSS) may be available to process data at lower data rates.*

4.2.7 Resolution- Spatial

Spatial resolution is the ability to sharply and clearly define the extent or shape of features within an image. It describes how close two features can be within an image and still be resolved as unique. All candidate systems, except older commercial systems, can meet spatial resolution requirements defined for this scenario. The TacSat system would need to be designed to meet these requirements.

4.2.8 Resolution- Spectral

Spectral resolution requirements were defined by the tactical user. The threshold requirement is for panchromatic only while the objective requirement includes middle/far infrared. All current systems can carry payloads that meet these spectral resolution requirements.

4.2.9 Interoperability

All systems must be interoperable within the FORCEnet Grid. All save some commercial systems, are interoperable.

4.2.10 Availability- System

Commercial systems usually have very high availability rates. The exception is the potential for intentional damage by hostile forces. Commercial satellites availability is subject to the owner’s discretion and usually requires a long contracting process unless they are untasked at the time. Global Hawk failure rate is about 27%, that is, about 1 of every 4 Global Hawks sent to theater will fail. Whether gaps exist is subject to unplanned events.

4.2.11 Availability- Link

All current systems meet link availability requirements.

4.2.12 Access and Control

Currently, a gap exists in that the tactical user cannot access or control imagery assets within the required time. The use of VMOC would allow the tactical user to have virtual control, as specified by the chain of command, in near real time.

4.2.13 Data Delivery Time

Currently, data through national sensors as a result of priorities for imagery in other theaters may take hours to get to the tactical user. Data delivery time from commercial sensors is a best unreliable and at worst unavailable. Global Hawk delivers imagery data quickly when within LOS (~ 500 Miles) but is constrained by the availability of overhead resources when beyond LOS. TacSat is a feasible alternative to mitigate this gap and provide reliable data delivery time to the tactical user.

4.2.14 Capacity

One to two Mbps for secure voice and data are required to support tactical communications. All systems considered can support this requirement so the question remains availability. If commercial systems are not available then TacSat must be designed to meet this capacity requirement.

4.2.15 Duration (years)

All systems meet duration requirements though Global Hawks cost rises over time due to cost of staff. Overhead sensors can be turned on and off easily while Global Hawk requires expensive staff changes.

4.2.16 Availability-Launch or Service Request Time (Days from Request)

Commercial sensors are always available if operational commanders decide to make them available. Global Hawk requires transport of ground station and personnel and set up time in theater. The time depends on distance of Global Hawk home base to operational base and availability of air transport for ground station and personnel.

4.2.17 Cost-Theater Lift Impact

Overhead systems do not require any lift to the theater. Global Hawk operates in several modes but all require some level of lift to the theater (ground support equipment, operating staff). For long periods of operations (1-3 years) significant lift would be required. For long periods of operations Global Hawk requires 2 C-141's or 2 C-17s with 6 or 11 meter antenna. This exceeds the required maximum lift requirement (1 C-17) so a gap exists. TacSat is a feasible alternative to mitigate this gap.

4.2.18 Cost-In Theater Staff Support

All systems require staff to analyze imagery so it is assumed that staff numbers will be common for all systems. Global Hawk requires an additional 3 staff in the launch and recovery element, about 5 in mission control, plus about 5 others to maintain equipment. Given a watch rotation every 8 hours a total staff of about 39 is required. This exceeds the staff maximum requirement and therefore a gap exists. TacSat is a feasible alternative to mitigate this gap. (Table 4-5)

Table 4-5. ISR Performance/Gap Summary

Performance Parameter	Commercial	Global Hawk	TacSat
Coverage- (Temporal Resolution) for each AoI		4 GH required	
Coverage- regions (LAT)			
Coverage- regions (LONG)			
Coverage-# of Areas		4 GH required	
Coverage -Restricted Airspace			
ISR Downlink Capacity (In theater)			
Command Control			
(Spatial) Resolution			
Spectral Resolution			
Interoperability			
Availability- System			
Availability- Link			
Access and Control (from theater)			
Data Delivery time (from request to delivery)			
Capacity			
Duration (years)			
Availability (Launch or service request time)			
Cost-Theater Lift Impact			
Cost-In Theater staff support for ground ops			

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5.0 TACSAT SYSTEM ANALYSIS

This section outlines a high level model that will give insight into the key technical parameters describing an operational TacSat system. These values will provide insight into the feasibility and performance of TacSat and provide inputs to the cost analysis that follows.

The approach followed was to first develop estimates for key system parameters based on rules of thumb. These were used as entering arguments for more detailed analysis. The results of this analysis were then rolled into a second tier, more detailed set of models. These models should provide reasonable fidelity for the initial determination of the cost estimating relationships for the cost model.

Overall System Parameters

To begin the analysis estimates of the key system parameters for mass, volume, body area, linear dimension and moment of inertia were developed. These initial values served as entering arguments for high level payload analysis which in turn provide data for a more detailed analysis of the key BUS subsystem budgets for power, mass, and volume. These models once established can be refined and enhanced to support more detailed analysis or to investigate different alternatives.

Initial design parameters for a satellite are given by well known rules of thumb or relationships that have been demonstrated to hold on previous satellites. These relationships use the dry mass of the spacecraft as an initial input and derive values for volume, linear dimension, body area, and moment of inertia. Although TacSat is a new breed of satellite the rules of physics and properties of materials that underlie these relationships still hold.

The key is determining a reasonable value for dry mass. A great deal of historical data on spacecraft dry mass is available for previous space systems. Ideally one would start with a value for dry mass given by this historical data. Fidelity is gained by organizing this historical data by satellite type as is done in Appendix A of Space Mission Analysis and Design (SMAD). TacSat, however, is intended to be an entirely

new breed of satellite that will be simpler, lighter and cheaper than past satellites. There is no historical data available for this type of satellite.

This problem was solved by taking values for types of spacecraft that are closely related to TacSat and adjusting them to arrive at reasonable first estimates. The validity of these estimates will be tested and their fidelity improved as subsystems are examined in greater detail and the systems analysis is iterated. TacSat will be called upon to perform two key types of tasking. The first is communications and the second is remote sensing. In addition, because TacSat is supposed to be simpler and lighter than typical satellites it has much in common with a class of satellites known as light SATS. Data for dry mass was taken from SMAD Appendix A for each of these three types of satellite. The data was then adjusted by increasing values for the light SAT by one standard deviation and decreasing the values for the communications and remote sensing satellites by one standard deviation. Average values were taken from these to produce a dry mass for the notional TacSat system. The results of these calculations are shown in Table 5-1.

Table 5-1. TacSat system parameters

Type of Satellite	Average Dry Mass (kg)	Standard Deviation (kg)	Corrected dry Mass (kg)
Light SAT	109	+ 31.3	140.3
Communications	816	- 389	427
Remote Sensing	1412	+ 605	807
Composite (Average) TacSat Estimate			458.1

The given value of dry mass of 458 kg seems like a reasonable first approximation.

Table 5-2 shows the key parameters for an initial spacecraft design, the relationships used to estimate them and the values derived based on a loaded mass of 558 kg for the notional system. This includes the addition of 130 kg of propellant.

Table 5-2. Key parameters for an initial spacecraft design

Loaded Mass = M (kg)	Propellant Mass (kg)	Dry Mass (kg)
588.5	130.4	458.10

Characteristic	Estimate	Value
Volume (cu.m)	V = 0.01(M)	5.89
Linear Dimension (m)	s = 0.25(M)^0.333	2.05
Body Area (sq. m)	A = (s)^2	4.21
Moment of Inertia (kg-sq.m)	I = 0.01(M)^1.6666	19.19
Loaded Mass (kg)	M	588.50

Mass Budget:

Using the same methodology outlined above for deriving the initial estimate of dry mass; percentages of dry weight were calculated for each subsystem. These are summarized in Table 5-3.

Table 5-3. Percentage of each subsystem dry weight

Item	% of Dry Mass
Payload	23
Bus Subsystem	
Structure	17
Thermal	2
Power	21
TT&C	6
ADCS	7
Propulsion	4
Margin	20
Total	**100**

Using these percentages the spacecrafts first mass budget was generated as shown in Table 5-4.

Table 5-4. Spacecraft first mass budget

Element	Estimating relationship	Value (kg)
Payload	0.23x(Dry Mass)	105.36
Bus subsystems		
Propulsion	0.04xDry Mass)	18.32
Attitude Control	0.07x(Dry Mass)	32.07
TT&C	0.06x(Dry Mass)	27.49
Thermal	0.02x(Dry Mass)	9.16
Power	0.21x(Dry Mass)	96.20
Structure	0.17x(Dry Mass)	77.88
Margin	0.24x (Dry Mass)	109.94
Dry mass Total	**From previous calc**	**458.10**
Propellant	From previous calc	130.40
Loaded Mass	Same as dry with no prop	588.50
Kick stage	Assume not used	0.00
Injected mass	Same as dry with no kick	588.50
Adapter		20.00
Boost weight		608.50

It is worth noting here that the nominal boost weight for FALCON I is exceeded by approximately 38 kg.

Power Budget:

Using rules of thumb as outlined in SMAD (page 316) an initial power budget was constructed. The payload power is used as the entering argument which, as a rule of thumb, typically consumes about 40% of the total satellite power. From this a total power was calculated. Based on that total power and the rules of thumb governing power usage in a satellite the initial power budget in Table 5-5 was created.

Table 5-5. Initial power budget

Initial Power Budget		
Subsystem	**Fraction of Total**	**Power (W)**
Payload	0.4	80
Propulsion	0.05	10
Attitude Control	0.15	30
Communications	0.05	10
Command and data handling	0.05	10
Thermal	0.05	10
Power	0.3	60
Structure	0	0
Sub total		210
Margin	0.25	50
Total		**260**

5.1 ORBIT AND CONSTELLATION

Selections of optimal orbit types and constellation sizes are critical parts of the system engineering process. In the context of the Philippine Sea scenario imagery requirements and communications requirements that could potentially be met using TacSat were derived. (Section 4.2 Gap Analysis). The orbit and constellation selection process was an iterative process (as outlined below) aided by the use of a modeling and simulation tool, standard reference Satellite Tool Kit (STK), which has led to the final recommendations for orbits and constellations. The entire modeling and simulation approach in contained in Appendix B. The established process for selecting orbits is: [Larson W, Wertz J 1999]

1) Select orbit types (parking, transfer, space-referenced, earth-referenced)
2) Determine orbit related mission requirements for both imagery and communications
3) Assess applicability of specialized orbits
4) Conduct constellation size/orbit design trades
5) Assess launch and disposal options
6) Evaluate growth and replenishment options
7) Create Delta V budget
8) Document orbit parameters, selection criteria, and reiterate as required.

5.1.1 Selecting Orbit Types

Step one, selecting orbit types, is clear in that this mission will require only an earth-referenced orbit selection. It is conceivable that a parking orbit will be used prior to disposal but for the purposes of this study, it is assumed that the satellite will be de-orbited shortly after mission life and will not address the issue of parking orbits. GEO will not be considered as an option for tactical satellites due to excessive cost of launch, unsuitability for ISR missions, and high link budget requirements. HEO will be discussed briefly for the communications mission, but again, the costs associated with high energy orbits and radiation hardening is of great concern for a viable TacSat concept.

5.1.2 Orbit Mission Requirements

Orbit characteristics are closely tied to payload capability but altitude and inclination are critical factors in any case. This paper will focus on imagery requirements and communications relay requirements for remote sensors. Orbit affects ISR payload coverage, imagery resolution, communications package sensitivity, environmental survivability, launch capability, ground communications, orbit lifetime, and even legal or political constraints. Orbit also impacts link budget and availability for communication relay systems.

The analysis to this point and the resulting requirements provide several key parameters relevant to the constellation and orbit analysis. These key parameters for imagery include temporal resolution, area coverage, and spatial resolution. In the simplest of terms the orbits need to support the acquisition of clear images over the Philippines operational areas at least 6 times per day and provide adequate dwell time for imagery data downlink.

The key parameters for communications and /or communications relay includes dwell (persistence), area coverage, and link/power budget. While TacSat is kept is kept in Low Earth Orbit (LEO) to reduce launch costs and to reduce the communications power requirements, all aspects of performance and cost were considered. The objective

of the modeling effort is to determine the optimal orbits and constellations with respect to total cost and payload performance.

Mission requirements also include the ability to pass control of the satellite payload to the tactical commander. This involves the added complexity for timing and managing uplink commands to the satellites and receiving downlink data as the LEO satellites pass over head.

5.1.2.1 Coverage

Coverage is defined to include earth location of interest, continuity, frequency, duration, field of view, and ground track. These requirements are impacted by orbit type, altitude and inclination. As discussed earlier, for the imagery requirement, the orbit type is limited to LEO. Altitude selection is discussed in a later section.

Mission requirements (for imagery) derived from the scenario dictate coverage in the Philippine operational area between 20^0 north and 7° south of the equator. Specifically, coverage in several areas is required at least once every four hours to meet threshold and once per hour to meet objective. Establishing inclination for a LEO is based on maximizing coverage in this region and the optimal inclination is no greater then 20^0. This insures the most frequent coverage of a targeted area of interest.

Figure 5-1 is a snapshot from an STK model simulation run. It shows a sample ground track for a single satellite traveling in a circular orbit at 400 km altitude and 20^0 of inclination. There are several example targets spread over the AOR that are separated by thousands of kilometers. Each parallel track could be separated by as much as 1000 km. With a potential sensor FOV of as little as one tenth of the track separation, a method for pointing the sensor is required. This is covered in the payloads section below. Due to angular constraints of the payload, pointing alone may not provide adequate coverage. This will drive an increase in the size of the constellation.

Figure 5-1. Sample ground track of scenario AOR

Mission requirements for communications and communication relay may require coverage 24 hours a day/seven days a week over the entire land and sea entire operational area. Here too, a balance must be struck between antenna beam width, altitude, and power requirements.

5.1.2.2 Temporal Resolution (Revisit Rate)

Altitude and inclination can affect the frequency that a single satellite passes over a target but they are not usually considered drivers for the overall revisit rate. Defined as the number of times a specific target is accessible by the total constellation in a period of time, the revisit rate is an orbit mission requirement that is most greatly affected by the number of satellites in a constellation. To meet greater operational mission requirements, more satellites must be added to the constellation, thereby directly driving cost, and leaving room for substantial trade space.

Revisit rate is considered for both imagery and communications relay. With imagery, it reflects the frequency that a tactical commander needs to update situational awareness of a given target. For static or slow moving targets, the rate can be low, but for more dynamic situations, a higher revisit rate may be required. Observing the number of times a single satellite passes through the AOR at various altitudes within the predefined constraints, STK shows the number of passes stays relatively steady at between 14-15 per day for altitudes from 400 km to 550 km. Varying the inclination from baseline by +/-5 deg does little to affect the number of passes per day either. This provides a good multiplicative factor for determining the number of satellites required in the constellation to meet a given revisit rate. In order to meet the requirement of one pass per hour, two satellites would be required in the imagery constellation. They would be in the same orbit but the ascending node would be 180 deg out of phase.

5.1.2.3 Link Establishment

Regardless of the specific mission, all TacSat's must establish a communications link with ground stations for satellite and payload control and for imagery data downlink. Aside from environmental and atmospheric conditions, the two most important variables affecting link establishment are distance between transmitter and receiver and "time in view". The impact of free space path loss on uplink and downlink signals is most greatly affected by altitude and angle of incidence. (Figure 5-2)

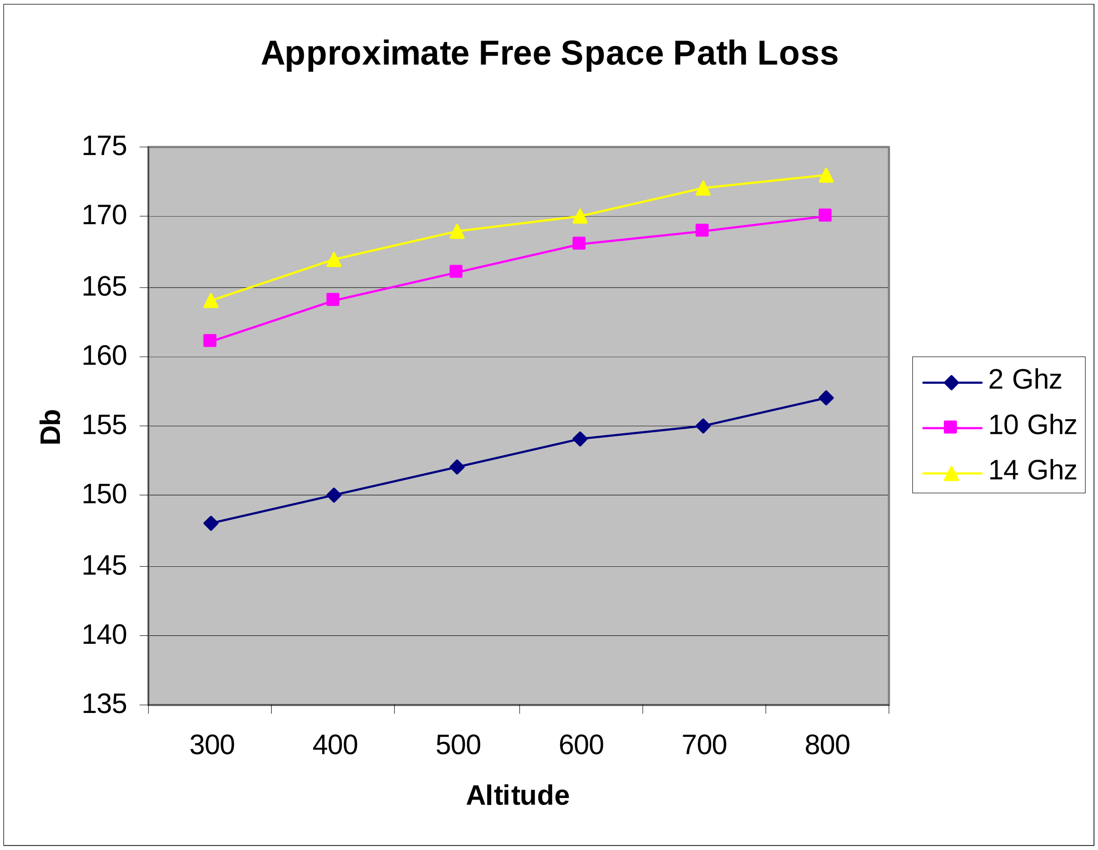


Figure 5-2. Free Space Path Loss

Yet another issue challenging the ability to establish a persistent link is the length of time that the transmitter can access the ground station. At such low altitudes, there may not be sufficient time in a given pass to transmit all of the data currently in storage. Furthermore, a single tactical ground station local to the AOR may not be in position to receive data from the current pass, causing further delay in transmission to the end user by the length of time it takes to make a complete orbit. Conversely, the ground station may not be in position to transmit timely housekeeping data to a passing satellite, thereby delaying reaction by one orbit cycle (roughly 1 hour 30 minutes). For this reason, actual spacecraft flight would most efficiently be handled by existing control facilities which utilize relay satellites to maintain constant control and monitoring.

For communications relay, arguably an infinite rate or continuous access is desirable. However cost constraints on the TacSat program limit the orbit selection and size of the constellation, so other relay methodologies must be used. In the case of

relaying data from a remote sensor, the sensor would need to store the data until uplink could be established. Similarly, if immediate relay operations are not attainable because the ground station is not simultaneously in the satellite's footprint with the sensor, then the satellite would need to provide store and forward capabilities as well or utilize other methods to pass the data such as relaying to an existing GEO constellation such as Track and Data Relay Satellites (TDRS).

5.1.3 Specialized Orbits

The Highly Elliptical Orbit (HEO) was modeled for consideration with respect to communication and communication relay requirements. In this scenario, a DADS array was the simulated target off of the west coast of Mindanao in the Sulu Sea. It was determined that a constellation of three satellites could maintain near 24x7 persistent coverage over the target requiring relay services. Each satellite had an apogee altitude of 32,500 km and a perigee altitude of 600 km at an inclination of 8 degrees. Each satellite orbit's Right Ascension of the Ascending Node (RAAN) was 120 degrees out of phase with its neighbor and the orbit planes are 120 degrees out of phase. Generally speaking, coverage of this magnitude would best be provided by existing GEO communications satellites, assuming that sufficient channels are available for all contingency requirements. Due to the HEO's high apogee altitude, there would be little if any reduction in required power of the ground terminal relative to up-linking with a GEO satellite. Likewise, there would be a corresponding increase in power required on the satellite for downlink back to the mission center. The cost of a HEO launch is also much greater than a LEO launch. For TacSat to remain a truly low cost solution, specialized orbits are cost prohibitive.

5.1.4 Constellation Size/Orbit Design Trades

The entering arguments for determining constellation size and orbit type include mission environmental constraints, requirements, and payload performance. The environmental factors previously evaluated included space radiation, space debris, and

the consequences of altitude versus orbital decay. Orbital constraints are considered based on the assumption that low cost is paramount and therefore spacecraft hardening is to be avoided.

Since the Van Allen belt (South Atlantic Anomaly) dips to only 320 km between 35^0 S and 60^0 S a constraint is set at either 35^0 inclination or an altitude of less then 320 km. In this scenario the optimal inclination is about 20^0 so a higher altitude of up to about 800 km can be considered although space debris is least severe at altitudes under 550 km.

While the lowest possible altitude is desirable to reduce launch cost and maximize imagery payload performance, a constraint that TacSat must last at least one year dictates a minimum altitude of 400 km to avoid rapid orbit decay due to atmospheric drag. This constraint may push the satellite to higher altitudes and/or drive the architecture to include a propulsion system and extra fuel in order to maintain altitude as well as momentum wheels to maintain steady flight. Drag effects are strongest for low mass satellites with large frontal areas or low ballistic coefficients. The basic formula for ballistic coefficient is (B_C) = $\frac{m}{C_D A} \approx 116 kg/m^2$ where: m = 450 kg for the initial estimate, C_D = 2.2 (avg low value from SMAD); and A = frontal area of the satellite, which is estimated to be 1.8 m^2. At the base target height of 400 km, altitude (*a)* = (6,378.14 + 400) * 1000 = 6,778,140 m and atmospheric density max (*p*)= 5.04E-11 kg/m^3 during max solar activity. This is entered into the below equation to get a rough estimate of the change in altitude per revolution. This value can be used in the propulsion section to determine ΔV required for orbit maintenance.

$$\Delta a_{rev} = (-2 * \pi * C_D * A * p * a^2)/m$$

or

$$\Delta a_{rev} = (-2 * 3.14 * 2.2 * 1.8 * 1.05E - 11 * 6{,}778{,}140^2)/450 = -125.63m$$

The following spreadsheet (Figure 5-3) calculator shows the impact of mass, drag coefficient, and spacecraft cross section on Ballistic Coefficient. It shows that minimizing spacecraft cross section is critical in overall design.

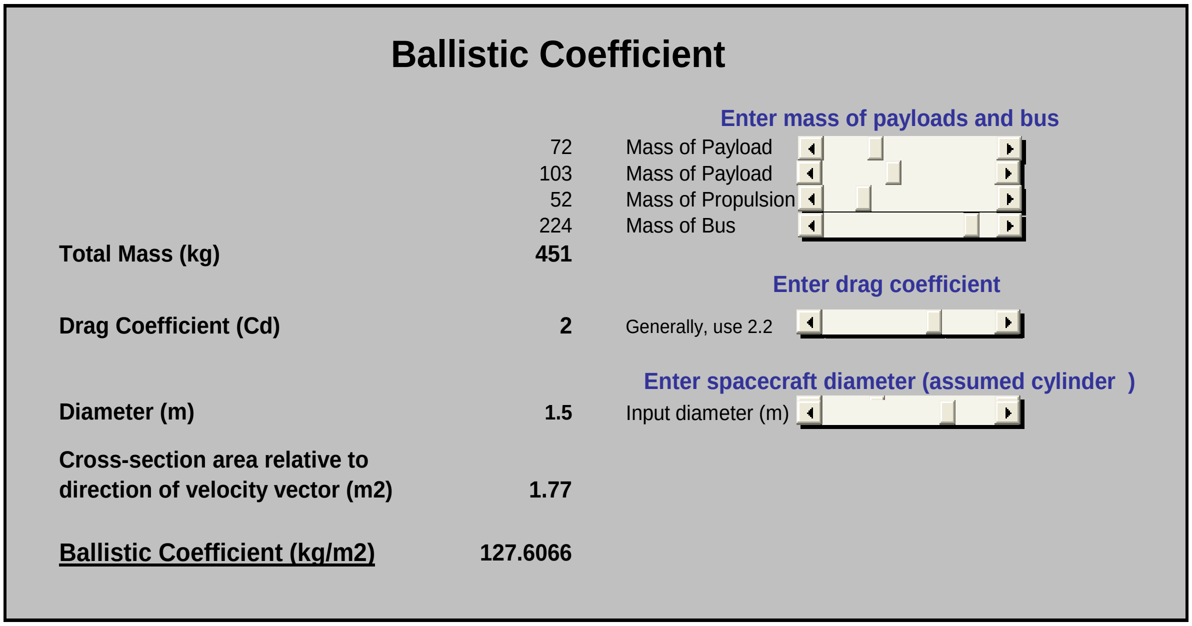


Figure 5-3. Ballistic Coefficient {Active excel model}

Estimated orbit life is approximated by the equation $L \sim H/\Delta a$ where H is atmospheric scale height of -87.5 km at 400 km. $L \sim (87.5 * 1000) / -125.63$ or 697 revolutions or about 45 days. A spreadsheet calculator is provided to assist with future investigation of the impact of satellite size and shape, orbit altitude, and weight on system orbit lifetime. A graph of lifetime vs. altitude for a given configuration is presented below to show the effects. Of note, increasing altitude from 400 km to 450 km increases orbit lifetime by almost 40 days at solar max and reduces the loss of altitude per revolution by 45%. This corresponds to a reduction of fuel required to maintain altitude. As will be shown in the payload section, this increase in altitude slightly improves the FOV and does not keep the imager from meeting resolution requirements. (Figure 5-4)

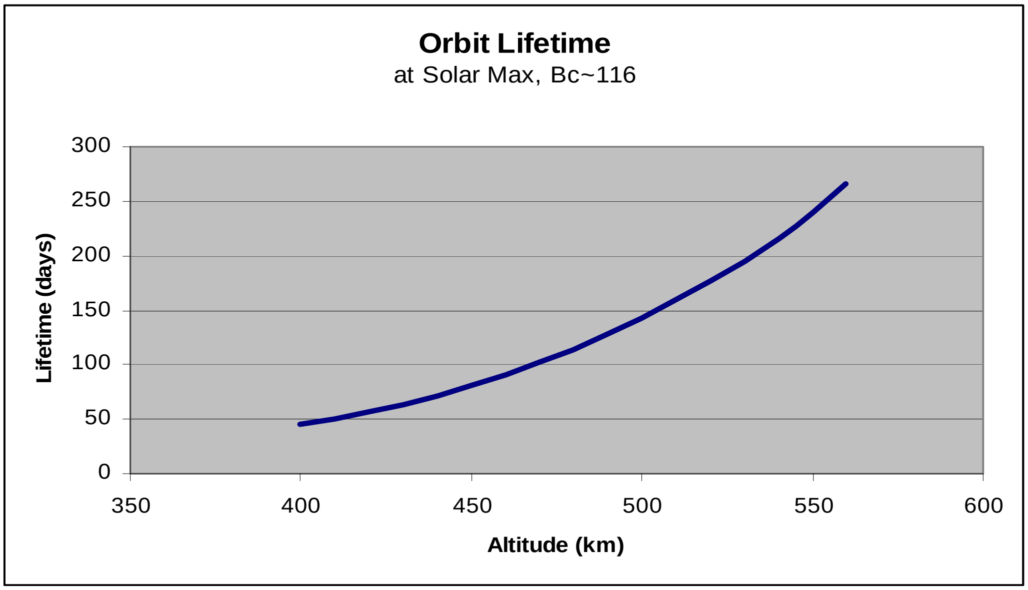


Figure 5-4. Orbit Lifetime

In summation, the environmental constraints set orbit constraints at between 400 and 550 km at between mission-specified 15^0 to 20^0 inclinations.

Temporal resolution requirements are keys in determining how many satellites are required in a constellation and are key trade space parameters for both imagery and communication payloads. As mentioned in the temporal resolution section, the required revisit rate within the AOR was achieved with two satellites. Table 5-6, generated from an STK access summary report, shows coverage times for the entire AOR over a 24 hour period, treating the AOR as a single target. A constellation of two LEO orbiting satellites with 400-km altitude, inclination 200, and separation of 1800 RAAN have a revisit rate approximately 40 minutes.

Table 5-6. AOR Revisit Times

Access Summary Report				
AOR-To-ISR_Bird1				
Access	Start Time	Stop Time	Duration (min)	Revisit Time (hrs)
1	0:00:00	0:08:55	8.9	
2	1:28:24	1:46:39	18.3	1:19:29
3	3:06:35	3:23:57	17.4	1:19:56
4	4:45:02	5:01:18	16.3	1:21:06
5	6:23:24	6:39:04	15.7	1:22:05
6	8:01:38	8:17:31	15.9	1:22:34
7	9:39:36	9:56:33	16.9	1:22:05
8	11:17:15	11:35:09	17.9	1:20:42
9	12:54:54	13:13:05	18.2	1:19:45
10	14:32:50	14:50:38	17.8	1:19:44
11	16:10:52	16:28:13	17.4	1:20:13
12	17:48:55	18:05:57	17.0	1:20:42
13	19:27:09	19:44:00	16.9	1:21:12
14	21:05:14	21:22:34	17.3	1:21:13
15	22:43:00	23:01:06	18.1	1:20:25

Access Summary Report				
AOR-To-ISR_Bird2				
Access	Start Time	Stop Time	Duration (min)	Revisit Time (hrs)
1	0:49:56	1:07:35	17.7	
2	2:28:00	2:45:13	17.2	1:20:25
3	4:06:08	4:23:02	16.9	1:20:56
4	5:44:22	6:01:17	16.9	1:21:19
5	7:22:19	7:39:58	17.6	1:21:03
6	9:00:01	9:18:17	18.3	1:20:03
7	10:37:47	10:55:59	18.2	1:19:30
8	12:16:01	12:33:16	17.3	1:20:02
9	13:54:28	14:10:39	16.2	1:21:12
10	15:32:49	15:48:28	15.6	1:22:09
11	17:11:03	17:26:59	15.9	1:22:35
12	18:49:00	19:06:01	17.0	1:22:01
13	20:26:38	20:44:35	18.0	1:20:37
14	22:04:17	22:22:30	18.2	1:19:42
15	23:42:14	0:00:03	17.8	1:19:44

In addition, the parameters of the selected orbits provide critical information needed to complete the analysis of other subsystems in the TacSat system. Key information includes launch windows, periods of eclipse, and height above ground. As mentioned in the introduction, there are two overriding issues in determining the feasibility of a TacSat system. The first is cost and one of the key cost estimating relationships for imagery payloads is aperture. This is determined by a combination of required ground resolution and altitude. Altitude also is important in determining how much power needs to be transmitted to close the link for a communications satellite and power requirements in turn drive mass. Mass is the primary parameter in the cost estimating relationship for determining the cost of a communications payload. The required power and resulting mass are also cost drivers for the satellite bus. These are greatly influenced by the amount of time that the satellite is in eclipse. Eclipse time determines the amount of time that satellites solar panels are out of view of the Sun. (Table 5-7)

Table 5-7. Lighting definitions

Lighting Condition	Description
Direct Sun	Total sunlight.
Penumbra or Direct Sun	Partial or total sunlight.
Penumbra	Partial sunlight.
Penumbra or Umbra	Partial sunlight or total shadow.
Umbra	Total shadow.
Umbra or Direct Sun	Total shadow or total sunlight

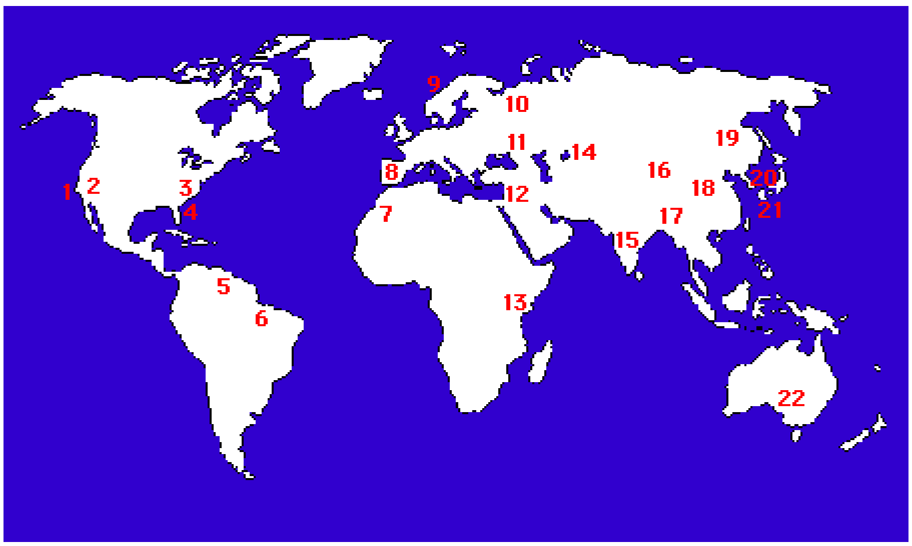
These lighting conditions coupled with power requirements determine battery size. The orbit also determines the amount of time the satellite's solar panels are viewed by the sun and that determines the size of the solar panels. The size of the solar panels and batteries are very important cost drivers for the bus. Umbra is equivalent is where the satellite is in total shadow which happens approximately 16 times per day for about 36 minutes. Preceding and following each umbra is an 8 second penumbra time period. Table 5-8 gives half-day umbra and penumbra times for a single satellite in circular orbit at 400 km and 20^0 inclination.

Table 5-8 . Half-day umbra and penumbra times

	Lighting	Start Time	Stop Time	Duration (min)
	Penumbra	0:07:20	0:07:28	0.135
1	Umbra	0:07:28	0:43:27	35.98
	Penumbra	0:43:27	0:43:35	0.135
	Penumbra	1:39:06	1:39:14	0.135
2	Umbra	1:39:14	2:15:13	35.99
	Penumbra	2:15:13	2:15:21	0.135
	Penumbra	3:10:52	3:11:00	0.135
3	Umbra	3:11:00	3:46:59	35.99
	Penumbra	3:46:59	3:47:07	0.135
	Penumbra	4:42:38	4:42:46	0.135
4	Umbra	4:42:46	5:18:45	35.99
	Penumbra	5:18:45	5:18:53	0.135
	Penumbra	6:14:24	6:14:32	0.135
5	Umbra	6:14:32	6:50:31	35.99
	Penumbra	6:50:31	6:50:39	0.135
	Penumbra	7:46:10	7:46:18	0.135
6	Umbra	7:46:18	8:22:17	35.99
	Penumbra	8:22:17	8:22:25	0.135
	Penumbra	9:17:55	9:18:04	0.135
7	Umbra	9:18:04	9:54:03	35.99
	Penumbra	9:54:03	9:54:11	0.135
	Penumbra	10:49:41	10:49:49	0.135
8	Umbra	10:49:49	11:25:49	35.99
	Penumbra	11:25:49	11:25:57	0.135
	Penumbra	12:21:27	12:21:35	0.135

5.1.5 Assess Launch and Disposal Options

Major launch sites are listed below in figure 5-5. From a purely geographically point of view a launch site near the equator is ideal for TacSat so from this list the sites of Korou in French Guiana, Alcantara in Brazil, , and Italy's San Marco Range near Kenya are most suitable. From a political and military perspective sites in the United States are ideal which may include the current sites listed in figure 5-5 plus planned sites at Mojave California, Las Cruces New Mexico, and Lompoc California.



1 - Vandenberg	7 - Hammaguir	12 - Palmachim	17 - Xichang
2 - Edwards	8 - Torrejon	13 - San Marco	18 - Taiyuan
3 - Wallops Island	9 - Andoya	14 - Baikonur	19 - Svobodny
4 - Cape Canaveral	10 - Plesetsk	15 - Sriharikota	20 - Kagoshima
5 - Kourou	11 - Kapustin Yar	16 - Jiuquan	21 - Tanegashima
6 - Alcantara			22 - Woomera

Figure 5-5. Launch Sites [Space Today]

However, perhaps the most suitable site is the U.S. Army missile test range at Kwajalein Missile Range. At 10^0 N Latitude it is an ideal location for launching a satellite into orbit around the equator. It is the launch site choice for the current TacSat ACTD. (Figure 5-6)

Figure 5-6. Kwajalein Missile Range [From USAKA]

Another factor in determining the viability of a TacSat system is timeliness of launch. If the TacSat constellation can't be made available to a tactical commander in a reasonable time frame it will be useless. One of the drivers of timeliness is the availability of launch windows. Whatever other time constraints there may be, if launch windows are not available to get a sufficient number of TacSats into orbit, then the system will fail to have military utility. One possible solution to this problem can be addressed by the deployment CONOPS. Instead of using launch on demand concepts during an operation, TacSat would be deployed much the same as any other large headquarters support system. If available in a tactical commander's arsenal of tools, it would be deployed at the onset of an operation based on key decision points such as expected length of operation, overall area of operation, or size of operation in terms of military depth of involvement.

5.1.6 Document Orbit Parameters, Selection Criteria

After careful analysis of the mission requirements, payload parameters, the environment, and orbital mechanics the most feasible orbits are between 400 and 500 KM. Table 5-9 summarizes the issues and conclusions drawn from detailed analysis performed in the following sections.

Table 5-9. Orbit Summary Table

Factors affecting Orbit Altitude Selection			
Factors		**km**	**Comments**
Environmental Constraints			
Radiation	<	750	Van Allen Belts
Radiation (at Inclinations > 30 degrees)	<	321	N/A for Philippine scenario
Micrometeoroid Impacts	<	550	
Imagery sensor performance (see section 5.2.2)			
Spatial Resolution/ GSD-performance w/ 0.3 mirror diameter	<	400	For 1 meter GSD
Spatial Resolution/ GSD-performance w/ 0.45 mirror diameter	<	450	For 1 meter GSD
Temporal Resolution (from STK)	>	300	
Communications Sensor performance – CDL link budget	<	450	*1
Communications Sensor Performance – Data Rate	>	200	For up to 274 Mbps
Orbit Lifetime	>	400	
Time in view (from ground site)	>	300	w 20^0 elevation
Constellation Size Constraint	>	400	
Constraint -High	<	**450**	(w/ 0.4 aperture)
Constraint - Low	>	**400**	

*. Note: Link budget for TacSat II CDL at 300 km showed 7.4 db excess. Free space path loss is about 1.75 db per 100 km (10 GHz). Given a required 5 db margin the limit is reached at about 450 km.

Constellation size has the greatest ability to directly impact cost. The goal for imagery was to provide complete accessibility to the AOR within a 24-hour period and revisit the AOR up to once per hour. At altitudes between 400 and 500 km all points in the AOR are not accessible within a 24-hour period by one satellite, and the revisit rate falls short of the objective as shown in Table 5-6. Adding one more satellite to the constellation with a RAAN 180^0 from the first satellite provides the objective revisit rate. The ground track separation between the different satellites is also cut in half, providing complete accessibility to all points in the AOR within a 24-hour period. As discussed

previously for communications, 24x7 coverage can be obtained with a constellation of three satellites in HEO with each satellite's RAAN separated by 120^0.

5.2 PAYLOAD OPTIONS

The payloads that have been determined to have military utility in the previous sections of this paper fall into two major categories. The first is communication and the second is reconnaissance or ISR. The ISR payloads in turn fall into two sub categories: SIGINT payloads and imagery payloads. SIGINT payloads tend to be small, light, and not draw too much power. As such they are not cost drivers. In fact TacSats configured for either communications payloads or imagery payloads could carry an additional SIGINT payload with little cost impact. Consequently, this study will concentrate analysis on the imagery and communications payloads. It is beyond the scope of this analysis to do a detailed design of these payloads. Rather, it is the goal of the payload section to determine the top level characteristics of the payloads so that the key cost drivers can be identified and fed into the cost model. These top level descriptions also provide the required data to describe the bus and its subsystems in sufficient detail that its cost drivers can be identified and fed into the cost model.

5.2.1 Communications Payload Architecture

This section will explore the architecture alternatives for providing a communications link for the conceptual tactical satellite system. The SMAD process for specifying communication architecture was used as a basis for this analysis, but altered to accommodate the nature of this analysis as a feasibility study rather than a standard architecture design process. The process followed is detailed below:

1) Identify communications requirements from derived scenario requirements
    a. Identify data sources, end users, and locations
    b. Specify derived performance requirements
    c. Specify orbital constraints
2) Specify Alternate Communications Architectures
    a. Identify fielded LEO communications technologies

b. Identify links and ground station locations

3) Design and Size Each Configuration Link

    a. Identify currently available technology to leverage for rapid development

    b. Link budget analysis

    c. Specify concept of operations (CONOPS)

4) Identify Feasible Architectures

    a. Specify optimal technology candidates

    b. Specify additional development requirements

5.2.1.1 Identify Data Sources, End Users, and Locations

The requirements generation process identified a set of data sources, end users, and locations, based on the Philippines Sea Scenario, that require satellite communications bandwidth.

1) Field Commanders who require voice / medium data rate satellite communication bandwidth not available from national or commercial assets.

2) Navy ships requiring voice / medium data rate satellite communication bandwidth not available from national or commercial assets.

3) Unmanned/Autonomous Vehicles requiring high data rate channels for real-time control and data relay not available from national or commercial assets.

4) Autonomous Vehicles requiring small channels (< 9600 bps) for data burst communications in a less time sensitive decision loop.

5) DADS – The Deployable Autonomous Distributed System is a set of undersea sensors that rely on a gateway buoy with LOS RF or Iridium SATCOM link to send very small (~100 byte) bursts of data.

6) Field commanders and in-theatre HQs requiring real-time reception of the sensor data from the ISR payload.

5.2.1.2 Specify Performance Requirements

The process to identify and analyze potential candidates for the communications payload starts with the set of performance requirements derived from the scenario in section 3.5. These requirements serve as the filter to find a set of feasible candidates. Given the number of candidates identified, the need to either strength or relax these requirements is determined and the iterative process proceeds.

The requirements section calls for two types of communications payloads: one to support continuous, bi-directional data/voice transmissions for users in the op area and one to support the downlink of data for the ISR payload. The first design assumption made in this analysis is that the requirement for providing continuous communications from low earth orbit will require multiple satellites on the order of 25+ based on preliminary calculations. Due to this assumption, the bi-directional communications configuration is split into two sub-configurations. The Communications Repeater configuration will analyze the architecture for providing continuous communications with a constellation of satellites while the Store and Forward configuration will analyze the architecture for providing asynchronous communications with as few as one satellite.

5.2.1.2.1 Communications Repeater Assumptions, Requirements, and Users

The need for a tactical satellite acting as a communication repeater is established by the scenario based on four assumptions:

1) The demand for commercial satellite services during the natural disaster will be so high that they will not be available to augment MILSATCOM.
2) The effectiveness of national assets in Geo-Stationary orbits will be reduced due to environmental effects.
3) The availability of national assets may be reduced due to high demand in other theaters and or physical damage or loss.
4) Demand will exist for satellite communications supporting Anti-Jamming and Low Probability of Detection/Intercept that cannot be met by national assets.

The requirements that will drive the **Communication Repeater** payload analysis include:

1) Total payload weight < 105.3 kg or 232.1 lbs (23% of 458 kg)
2) Downlink/Uplink Data Rate of 1.0 Mbps
3) Access and Control in < 1 min
4) Interoperable with at least one type of ground terminal employed by the combatant commands and JTF
5) Continuous Coverage 24 hr/day
6) Constellation Availability of 97% and Link Availability of 95%
7) Bit Error Rate <= 10^{-7}

The potential end users for this configuration include:

1) Field Commanders who require satellite communication bandwidth not available from national or commercial assets.
2) Navy ships requiring satellite communication bandwidth not available from national or commercial assets.
3) Unmanned/Autonomous Vehicles requiring high data rate channels for real-time control and data relay not available from national or commercial assets.
4) DADS – The Deployable Autonomous Distributed System is a set of undersea sensors that rely on a gateway buoy with LOS RF or Iridium SATCOM link to send very small (~100 byte) bursts of data.

5.2.1.2.2 Store and Forward Assumptions, Requirements, and Users

The effective implementation of a tactical continuous satellite communications constellation in LEO will require many satellites to provide the 24 hr/day coverage stipulated in the initial requirements. The Tactical Satellite effort aims to provide rapid deployment of space based ISR and Communications anywhere on the globe. In keeping

with this aim, a Store and Forward communications payload could rapidly deliver satellite communications services, albeit with reduced requirements to a more select set of end users detailed below. Essentially, if the time and resources are not available to deploy a full satellite communications constellation providing continuous coverage in the op area, deploying fewer satellites configured with a Store and Forward payload will still provide a useful service.

The requirements that will drive the Store and Forward communications payload analysis are drawn from the Communications Relay above, with the following modifications:

1) Downlink/Uplink Data Rate of 9600 bps
2) Coverage based on number of passes per day given orbit

The potential end users for this configuration include:

1) Autonomous Vehicles requiring small channels (< 9600 bps) for data burst communications in a less time sensitive decision loop.
2) DADS – The Deployable Autonomous Distributed System is a set of undersea sensors that rely on a gateway buoy with LOS RF or Iridium SATCOM link to send very small (~100 byte) bursts of data.

5.2.1.2.3 ISR Payload Data Link Assumptions, Requirements, and Users

The need for a tactical satellite with ISR capabilities is detailed in both the Requirements section and the ISR Payload section. The need for a communications downlink to support the ISR Payload is a basic system requirement as it is assumed a launch and recover system would not provide the dissemination timeliness required.

The requirements that will drive the ISR Downlink communications payload analysis are drawn from the requirement for the Communication Relay above, with the following modifications:

1) Downlink/Uplink Data Rate capable of supporting the bit rate generated by the ISR payload, currently 274 Mbps.

2) Access and Control times capable of

   a. supporting real-time downlink of imagery during time over station, or

   b. supporting satellite cross-linking to communication relay satellite

3) Coverage requirements based on ISR constellation orbits

The potential end users for this configuration include:

1) Field commanders and in-theatre HQs requiring real-time reception of the sensor data from the ISR payload.

5.2.1.3 Specify Orbital Constraints

This analysis seeks to provide a feasible set of communications payload candidates for the conceptual tactical satellite system. While the standard communications satellite design approach would have the payload requirements drive the orbital selection, the primary driving requirements for this system are those associated with cost and time. Analysis performed in the previous sections has determined that a low earth orbit with an altitude in the range of 400 to 450 km is optimal for accommodating the constraints of a low-cost, imaging satellite system.

As such, altitude will drive many trades in the communications architecture design space. Altitude will drive time in view and transmission delays; time in view and antenna max angles will drive access times; access times will drive data rates, and so on.

Given the orbital altitude constraint, the transmission delay ranges and access time ranges will be specified for the low end of this range, 400 km. This altitude corresponds to a slant range varying with elevation angle, charted below.

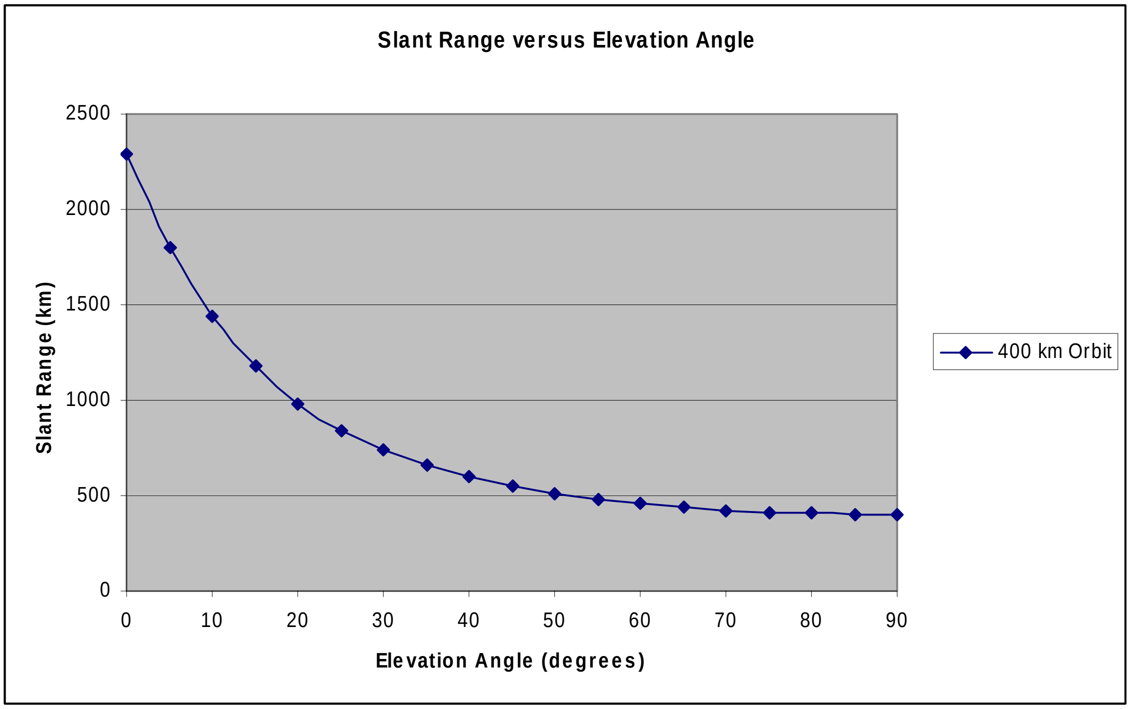


Figure 5-7. Slant Range vs. Elevation Angle for 400 km Altitude

The slant range varies from 2293 km to 400 km as the satellite comes over the horizon and back down. (Figure 5-7) This range, in turn, translates to a transmission delay varying with elevation angle charted below. The range of transmission delays at this altitude vary from ~7.64 to 1.33 milliseconds. (Figure 5-8)

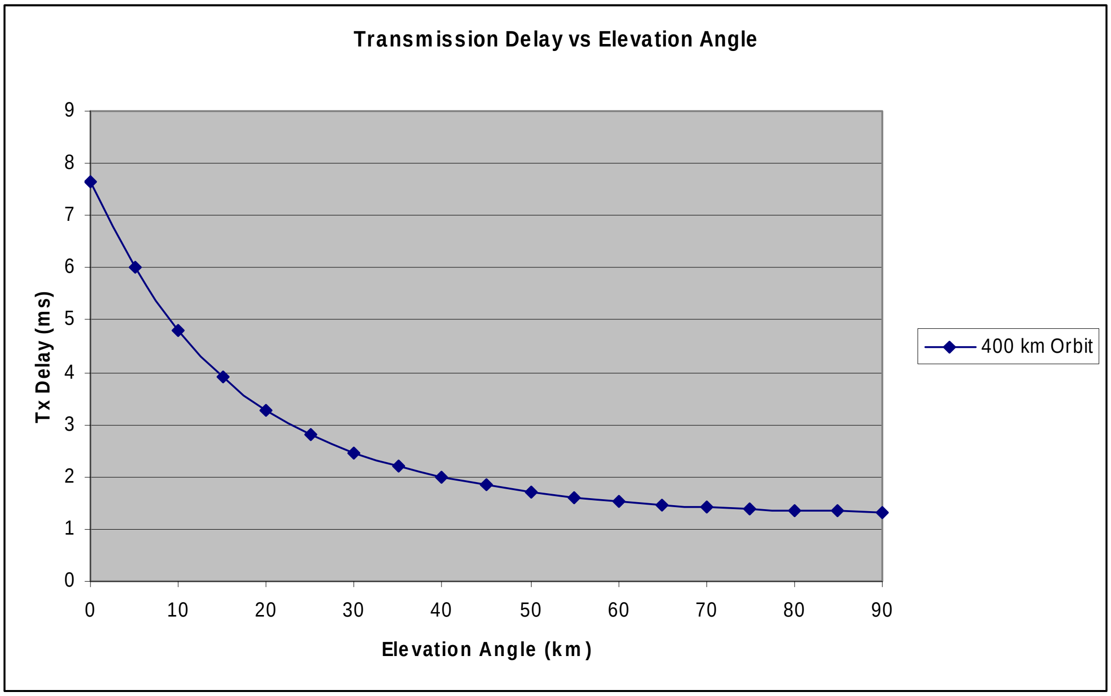


Figure 5-8. Transmission Delay vs. Elevation Angle at 400 km Altitude

Parameters considered include slant range, transmission delay specifications, access time, and angle constraints. Analysis is performed in the ISR Payload section that calculates the time in view values for the 400 km altitude. Considerations for providing communications payload constraints include elevation angle vs. time in view, nadir angle from the satellite, and the maximum slant range that the payload would have to close the link over. These values are specified in the Table 5-10.

Table 5-10. Orbital Communications Constraints

Elevation Angle (degrees)	0	5	10	20
Time in View (min)	10.17	7.91	6.21	4.03
Nadir Angle (degrees)	70.2	69.6	67.9	62.15
Max Slant Range (km)	2293	1804	1439	984

At this altitude, a zero degree elevation angle corresponds to a 70.2-degree nadir angle from the satellite. To utilize the entire 10.17 minute window would require a communications payload capable of closing a link over 2293 km with an antenna that supports a pointing angle of 70.2 degrees off nadir.

5.2.1.4 Specify Alternate Communications Architectures

In order to obtain an understanding of the technology base for these types of payloads, fielded systems providing communications services in low earth orbits were researched. System specifications are detailed below to assist in determining candidate frequency bands and equipment technologies for use in the tactical satellite communications payload architecture.

Globalstar and Iridium are two of the most technically, though not economically, successful systems, in the domain of LEO communication satellite systems. In the context of this scenario, the assumption is that commercial assets of this type are either saturated with use or the demand for military bandwidth exceeds that which the system can support. Both of these systems provide a solid historic technology baseline that helps determine initial parameters for the Tactical Satellite communications architecture.

The Globalstar satellite system is a LEO constellation of 48 satellites providing voice and low rate data channels to much of the globe. The system configuration is detailed in Table 5-11. [Wood L, 1999]

Table 5-11. Globalstar Satellite System Specification

Number of Satellites	48
Orbit	1414 km, 52 deg
Constellation Config	8 planes with 6 satellites each
Coverage	+- 70 deg Latitude
Period / Visibility	114 min / 16.4 min
Bus Mass	400 kg dry
System Power	1000 W from two solar panels
Access Method	CDMA / FDMA
Transponders (User)	1.610-1.6265 GHz Up / 2.4835 – 2.50 GHz Down
Transponders (Gateway)	5.091 –5.250 GHz Up / 6.70 – 7.075 GHz Down
Beams / Satellite	16
Beam Diameter	2254 km
Channels / Satellite	Up to 3000
Data Rate (Avg)	4.8Kbps Voice Channel / 9.6Kbps Data Channel

Table 5-12. Globalstar Link Budget [Gkizeli et al, 1999]

Down link

Parameter	Value
Carrier frequency	2·495 (GHz)
Satellite EIRP	17·41 (dB W)
Free space loss	−165·19 (dB)
Boltzman's constant	−228·6 (dB W/Hz K)
Terminal antenna G/T	−24·16 (dB/K)
Other losses	−1·5 (dB)
Noise density N_0	−204·4 (dB W/Hz)
C/N_0	54·84 (dB Hz)
Data rate	−39·83 dB bps (9600 bps)
E_b/N_0 (uncoded)	15·01 (dB)
E_b/N_0 (coded)	18·81 (dB)
Interface density I_0	−205·6 (dB W/Hz)
$E_b/(N_0 + I_0)$ (coded)	16·36 (dB)
Coherent comb.gain	3 (dB)
E_b/N_0 at spotbeam edge (−3 dB)	16·36 (dB)

Up link

Parameter	Value
Carrier frequency	1·625 (GHz)
Terminal EIRP	1·76 (dB W)
Free space loss	−161·5 (dB)
Boltzman's constant	−228·6 (dB W/Hz K)
Satellite temperature	26·63 (dB K)
Satellite antenna gain	14·6 (dBi)
Satellite G/T	−12·03 dB/K
Other losses	−1·5 (dB)
Noise density N_0	−202 (dB W/Hz)
C/N_0	55·36 (dB Hz)
Data rate	−39·83 dB bps (9600 bps)
E_b/N_0 (uncoded)	15·54 (dB)
E_b/N_0 (coded)	19·34 (dB)
Interface density I_0	−203·5 (dB W/Hz)
$E_b/(N_0 + I_0)$	17·01 (dB)
Rake receiver gain	1 (dB)
Thermal noise margin	1 (dB)
E_b/N_0 at spotbeam edge (−3 dB)	16·01 (dB)

The Department of Defense has contracted with Iridium to provide bandwidth through a dedicated gateway on the system as part of the Enhanced Mobile Satellite Service (EMSS). The technology used in the Iridium satellites has proven to be a relevant model for small, low-cost, mass-produced communication satellites. The specifications of the Iridium system are detailed in Table 5-13. [Wood L, 1999]

Table 5-13. Iridium Satellite System Specifications

Number of Satellites	66
Orbit	780 km, 86.4 deg
Constellation Config	6 planes with 11 satellites each
Coverage	Global
Period / Visibility	100 min / 11.1 min
Bus Mass	689 kg
System Power	1400 W from two solar panels
Transmitter Power	400 W
Access Method	TDMA / FDMA
Transponders (User)	1.616 – 1626.5 GHz Up/Down
Transponders (Gateway)	27.5 – 30.0 GHz Up / 18.8 – 20.2 GHz Down
Beams / Satellite	48
Beam Diameter	600 km
Channels / Satellite	1100 Duplex
Data Rate (Avg)	4800 bps / Channel

Table 5-14. Iridium Link Budget [Wood, L 1999]

Down link		Up link	
Parameter	Value	Parameter	Value
Carrier frequency	1·626 (GHz)	Carrier frequency	1·626 (GHz)
Satellite EIRP	27·41 (dB W)	Terminal EIRP	4·77 (dB W)
Free space loss	−164·5 (dB)	Free space loss	−164·5 (dB)
Boltzman's constant	−228·6 (dB W/Hz K)	Boltzman's constant	−228·6 (dB W/Hz K)
Terminal antenna G/T	−24 (dB/K)	Satellite temperature	26·5 (dB K)
Other losses	−1·5 (dB)	Satellite antenna gain	23·9 (dBi)
C/N_0	66·01 (dB Hz)	Satellite antenna G/T	−0·6 (dB/K)
Data rate	−46·99 dB bps (50 kbps)	Other losses	−1·5 (dB)
E_b/N_0 (uncoded)	19·02 (dB)	C/N_0	64·71 (dB Hz)
E_b/N_0 (coded)	22·82 (dB)	Data rate	−46·99 dB bps (50 kbps)
E_b/N_0 at spotbeam edge (−3 dB)	19·82 (dB)	E_b/N_0 (uncoded)	17·78 (dB)
		E_b/N_0 (coded)	21·58 (dB)
		E_b/N_0 at spotbeam edge (−3 dB)	18·58 (dB)

One interesting distinction between the two systems is the Globalstar constellation uses fewer satellites at higher altitudes, but is able to provide similar if not better service with lower overall weight and power requirements than the Iridium system. One reason is the system's use of a CDMA waveform that provides greater power efficiency over the channel. The CDMA waveforms spreads the signal over a wide frequency range at lower power resulting is much lower total power draw. Additionally, the reason identified as

the primary contributor to this difference is Globalstar satellites' higher orbit results in the possibility that more than one satellite may be in view at a given location on Earth and both the terminal and on-board satellite processors are designed to combine these signals to improve the quality. [Hirshfield, 1996]

5.2.1.5 Identify Communication Links

Identification of communication links includes discussion of general frequency band suitability and an examination of the Common Data Link (CDL) system.

5.2.1.5.1 Frequency Band Analysis

The potential technology candidate are not filtered specifically by the frequency bands they support, but certain bands are more suitable than other given the requirements for high data rates, antenna size, and the environmental considerations imposed by the scenario.

The VHF/UHF band is primarily employed for mobile applications in adverse environmental conditions, but the supported data rates are so low that they will only be able to support the Low Data Rate (LDR) applications in the Store and Forward configuration. [Larson W, Wertz J 1999]

The SHF band provides a more desirable range of spectrum to work with given the wide bandwidth supporting high data rates, inherent jam resistance and immunity to most weather conditions. The X band and Ku band are currently the most utilized frequencies in SHF. The U.S. military has designated portions of each band for military use only. While the X band provides better immunity to environmental effects and less free space path loss, the Ku band provides greater bandwidth to setup channels. Utilization of the Ka band has been growing since the late nineties, primarily for multimedia applications such as satellite internet services. [Exec Sum]

The EHF band holds great potential as a highly survivable and secure range of spectrum, though it suffers in adverse weather conditions. [Executive Summary of Commercial Satellite Communications Report] The high cost of development for this frequency range currently puts it outside the feasible set for a low cost tactical satellite.

Consideration is also given to the congestion of the frequency bands by commercial and national assets. The C, X and Ku bands are highly used by many commercial satellite operators to provide fixed satellite services. The Ka band is filling with commercial assets as well, given its ability to support higher data rates and smaller terminals. [Exec Sum] In the context of this scenario it is expected that many commercial satellite assets will be in a state of increased use, introducing much greater channel utilization concerns in those bands.

The X and Ku Bands currently constitute the spectrum frequencies with the lowest development costs that support the bandwidth and data rate requirements for the ISR downlink payload. A future tactical satellite system might utilize the Ka band if channel utilization becomes an issue in the lower bands or the need for even more mobile, or possibly man portable systems drives the technology costs down.

5.2.1.5.2 Identify Data Link Technology

Common Data Link

The Common Data Link program was developed in 1988 out of an earlier Air Force / NSA data link program as a standard communication architecture that would span all DoD Services. The CDL architecture was designed as a "full-duplex, jam resistant spread spectrum, point-to-point digital link" providing uplink data rates reaching 45 Mbps and downlink data rates reaching 274 Mbps. The CDL family has five classes detailed below. [Pike J, 2005]

- Class I: Ground/Airborne platforms up to 80,000 ft
- Class II: Ground/Airborne platforms up to 150,000 ft
- Class III: Ground/Airborne platforms up to 500,000 ft
- Class IV: Satellite terminals up to 750 nm
- Class V: Satellite terminal above 750 nm

The first use of off the shelf Common Data Link equipment in a low earth orbit satellite system will be on TacSat-2, planned for launch in late 2006 on a Minotaur I rocket. The system to be flown on this test platform is a modified L3 ABIT CDL radio

used in the Tactical Aerial Reconnaissance System (TARS) pod on the F-16 fighter. This implementation provides the full 274 Mbps bandwidth equipment. [Dewey RG, Bishop J 2005]

The Microwave Model Assembly (MMA) is the primary component of the ABIT CDL radio. The gimbaled antenna, and its accompanying diplexer and power amp, were removed and replaced by an electronically steerable array (ESA) antenna for the downlink and a patch antenna for the uplink. The chassis was physically extended to accommodate more room for the wiring harness and then rotated to fit the internal satellite space. This was basically the extent of the modifications and allowed the program to rapidly progress from an off the shelf airborne CDL system to a satellite based system. (Figure 5-9) [Dewey RG, Bishop J 2005]

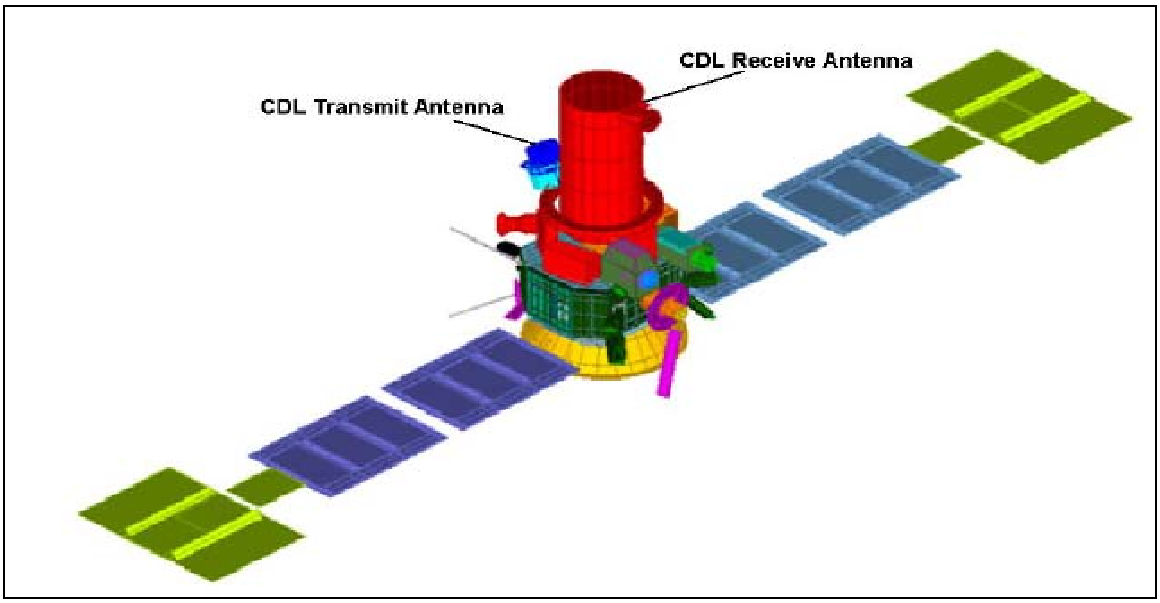


Figure 5-9. TacSat-2 Communications Antennas [Dewey RG, Bishop J 2005]

The need for hardening the payload environmentally was mitigated by the low earth orbit, staying below the radiation belts. The aluminum casing of the ABIT equipment was deemed sufficient shielding for the application and expected life cycle. Vacuum related issues were vetted and all components of the MMA were found to be suitable, though some antenna components were modified to ensure no exposed unsuitable materials. [Dewey RG, Bishop J 2005] Thermal heat sinking of the electronics was mitigated with the modified mounting orientation and the satellite bus provides heating for the downlink antenna. Finally, shock and vibration issue were mitigated by the ruggedness of both the MMA and antenna designs.

5.2.1.6 Ground Stations

The selection of the Common Data Link equipment as the primary radio link system must be made with the knowledge that an existing surface terminal is available that meets the requirements of the tactical scenario. The key requirements for the surface terminal include:

1) Mobile
2) Support high data rate downlinks
3) Support military encryption
4) Provide interconnections for modular external system

The Army's Modular Interoperable Surface Terminal, or MIST, was developed specifically for interface with the CDL link family. It employs a 6 ft parabolic dish in the standard configuration that provides 43 dB of gain in the X Band and 44 dB of gain in the Ku Band. It is capable of tuning frequencies from the L through the EHF bands, but the standard configuration is for use with X or KU bands. The terminal provides a selection of 10 W or 50 W output power. It supports BPSK modulation for the uplink and OQPSK modulation for the downlink with a BER of 1 E8 and convolution encoding FEC. The terminal supports data rates up to 200 kbps for the uplink and 274 Mbps for the downlink. The MIST ground station would be locating at the forward operating base,

which for the purposes of the scenario would be in the Philippine islands. (Figure 5-10) [L3, “Modular Interoperable”]

Figure 5-10. Modular Interoperable Surface Terminal (MIST) [Pike J, 2005]

The naval surface terminal for use with the Common Data Link family was originally called the Common High Bandwidth Data Link – Surface Terminal (CHBDL-ST), but has since been renamed simply as CDL-Navy, or CDL-N. The first physical embodiment of this system is in the USQ-123 terminal currently in production. The first installations were aboard aircraft carriers, with follow on installations on LHAs, LHDs, LPDs, and AGF/LCCs. The scenario envisions at least one Carrier Task Force in the area will be equipped with a CDL-N terminal. [Pike J, 2005]

5.2.1.7 Preliminary Link Budget Analysis

The preliminary concept of using CDL as the data link provided an initial set of ground terminal specifications based on MIST that allowed for an early estimation of the EIRP that would be required to close an uplink or downlink in the X and Ku Bands at the target data rates. Prior to defining the satellite antenna, the most challenging

communications link configuration would occur just as the satellite appears over the horizon from the ground terminal, at an elevation of 0 degrees. At an altitude of 400 km, this corresponds to a nadir angle of 70.2 degrees and a slant range of 2293 km. The downlink EIRP is determined by using these values and the MIST ground antenna.

Table 5-15. Initial Downlink Budget to Determine EIRP at X and Ku Bands

Item	274Mbps Downlink		45Mbps Downlink		Units	Comments
	X	Ku	X	Ku		
Frequency	7.4	11.8	7.4	11.8	GHz	
Equiv. Isotropic Radiated Power	30.5	34.4	22.7	26.5	dBw	
Propogation Path Length	2293	2293	2293	2293	km	Slant range at Elevation Angle = 0
Space Loss	-177.0427	-181.0957	-177.0427	-181.0957	dB	
Propagation & Polarization Loss	-0.3	-0.3	-0.3	-0.3	dB	Average value from SMAD
Receive Antenna Diameter	1.83	1.83	1.83	1.83	m	6ft MIST Antenna
Peak Receive Antenna Gain (net)	40.44728	44.50029	40.44728	44.50029	dBi	
Receive Antenna Beamwidth	1.550731	0.972492	1.550731	0.972492	deg	
Receive Antenna Pointing Error	0.5	0.5	0.5	0.5	deg	Assume 0.5 degree pointing error
Receive Antenna Pointing Loss	-1.247522	-3.172115	-1.247522	-3.172115	dB	
Receive Antenna Gain	39.19976	41.32817	39.19976	41.32817	dBi	
System Noise Temperature	135	135	135	135	K	SMAD Table 13-10
Data Rate	2.74E+08	2.74E+08	4.50E+07	4.50E+07	bps	
Eb/N0	14.03	14.08	14.07	14.02	dB	
C/N Density	98.41	98.46	90.61	90.56	dB-HZ	
Bit Error Rate	1.00E-08	1.00E-08	1.00E-08	1.00E-08	-	
Required Eb/N0	12	12	12	12	dB	OQPSK requires ~12 dB at 10^-18 BER
Implementation Loss	-2	-2	-2	-2	dB	
Margin	0.03	0.08	0.07	0.02	dB	

The downlink budget shows the EIRP necessary to close the link over the greatest slant range possible at the 400 km altitude for both frequency bands and both data rates. If the satellite power and antenna configuration can produce these EIRPs, they can close the link at any point during the time in view.

The uplink budget starts with the MIST station's high power mode, 50 W, and both the ISR Payload uplink data rate (200 kbps) and the SATCOM uplink data rate (45 Mbps) are used to calculate the antenna gain that must be obtained at the satellite.

The uplink budget shows that the high data rate modes for the SATCOM configuration in both bands require between ~5 and ~9 dBi of antenna gain, while the medium data rate modes for ISR commands can close the link with an extremely low signal.

5.2.1.8 Identify CDL Technology Candidates

The CDL data link family equipment currently provides one of the only low cost, relatively lightweight radio packages that support Extremely High Data Rates in the SHF frequency band. Multiple companies provide satellite data link equipment that is either designed for high data rates in large satellites or low data rates in smaller satellites. L3 Communications is the sole contract vendor for CDL compliant data link equipment sized for airborne platforms, which have been proven suitable for conversion to micro-satellite payloads. Table 5-16 provides a comparison of the primary off the shelf equipment available as of the writing of this paper.

Table 5-16. Potential Airborne Transitional Equipment Technology

	ABIT	**T-Series U**	**T-Series WB**
Modem Dims (m)	.251 x .343 x .419	.290 x .203 x .128	.305 x .320 x .404
Modem Volume (m^3)	.0361	.00754	.0394
Modem Wt (kg)	26.3	5.82	31.7
Modem Power (W)	272	150	750
Max Data Rate Down	274 Mbps	44.73 Mbps	274 Mbps
Max Data Rate Up	10.71 Mbps	44.73 Mbps	10.71 Mbps
Frequency Band	Ku / X	Ku	Ku

The L3 ABIT Data Link system is comprised of a Microwave Modem Assembly unit that houses the data modem, RF transceiver, and power amplifier sub-systems in a single chassis. The MMA is a 26.3 kg chassis that draws 272 watts at 28 VDC. It also includes a gimbaled parabolic antenna and waveguide array antenna, though these are not included in the size and weight specifications above.

The L3 T-Series Model U system is comprised of two modules, a Microwave Modem Assembly containing the data modem and a Link Interface Assembly containing the RF transceiver and power amplifier. The MMA is a 2.72 kg chassis and the LIA is a 3.18 kg chassis. The modules are interconnected and draw a total of 150 watts at 28 V DC. This system also provides a 5” omni-directional antenna assembly, though it is not included in the size and weight specifications above.

The L3 T-Series Model WB system is comprised of an Airborne Modem Assembly module containing the data modem and a Radio Frequency Equipment module

containing a RF transceiver and power amplifier. The AMA is an 18.1 kg chassis drawing 250 watts at 120 VAC and the RFE is a 13.6 kg chassis drawing 500 watts at 120 VAC. This system also includes a 9.5” 2-Axis gimbaled parabolic antenna, though it is not included in the size and weight specifications above.

These equipment specifications provide a reasonable baseline for root equipment that has been or could be modified for use in LEO communication satellites. The ABIT equipment was modified for use in the TacSat-2 program, although additional modifications of both the equipment and the platform will be necessary to arrive at a production design. The ABIT equipment would be the most likely candidate as the baseline design for a HDR Communications Relay or definitely as the ISR Payload Data Link. A LDR Communications Relay or Store and Forward configuration could be implemented with the lighter, lower data rate T-Series U equipment as the baseline for the design.

As this equipment was all designed for airborne applications, the antennas included in the off the shelf packages will not be optimal for a space based implementation. Just as with the TacSat-2 program, hard mounted electronically steerable antenna designs will provide the optimal solution, though software challenges in the steering of these antennas with mobile users will need to be addressed.

5.2.1.9 Identify Antenna Technology Candidates

The TacSat-2 team determined that a fixed parabolic antenna would not provide a suitable balance of gain and beam steering to be operationally effective.

5.2.1.9.1 TacSat-2 Electronically Steerable Antenna

An electronically steerable antenna design was specifically chosen for the satellite to lower complexity and aerodynamic impacts. This new downlink antenna was developed by ATK-Mission Research Corporation. It is made of 16 helical elements, each connected to an amplifier and phase shifter. The entire assembly is encased in foam to provide structural strength and protect the components. The antenna provides a 6.5 degree spot beam that can be steered within a 30 degree cone without the need for a gimbaled dish. [Dewey RG, Bishop J 2005]

5.2.1.9.2 X Band Phased Array Antenna

The X Band Phased Array Antenna (XPAA) was developed by Boeing's Phantom Works for NASA's Earth Observing satellite specifically for facilitating a high data rate downlink to support the gigabytes of data collected by the satellite each day. The antenna is comprised of 64 modules arranged in an 8 x 8 array. A circular waveguide, two antenna feeds, a phase shifter and two power amplifiers make up each module. The entire enclosure measures 12" x 13" x 2.9" and weighs 5.5 kg. The antenna can scan 60 degrees half-angle and has a 3 dB beamwidth of 10 degrees. It generates a LHCP polarization and draws approximately 58 watts of DC input power. The antenna has no moving parts, has proven highly reliable and space qualifiable, and currently is used to transmit over 160 gigabytes per day at 108 Mbps. [Perko K et al, 2002]

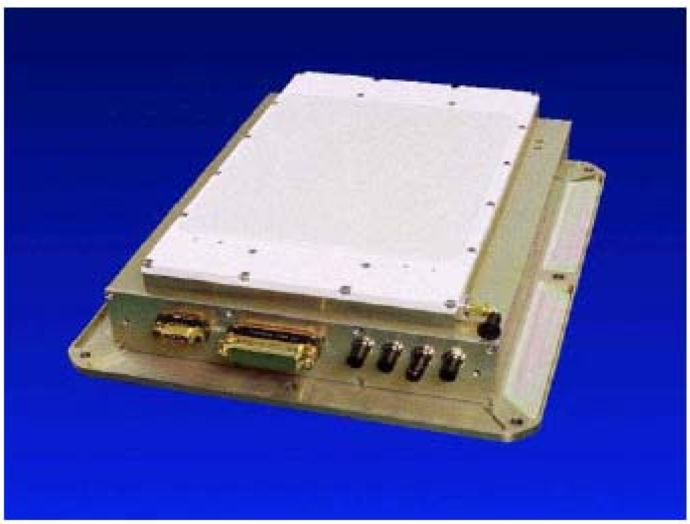


Figure 5-11. X-Band Phased Array Antenna [Perko K et al, 2002]

5.2.1.10 Detailed Link Budget Analysis

Additional link budgets are developed using the specification of the technologies identified in previous sections. Specifically, the XPAA antenna will be used as it gives the widest pointing angle of the two electronically steerable antennas identified to provide the EIRP necessary to close the high data rate downlink. The XPAA provides

the ability to electronically steer the beam up to 60 degrees off nadir. This translates to an elevation angle of approximately 22 degrees and a slant range of 895 km.

Table 5-17. Downlink Budget for 274 Mbps (ISR) and 45 Mbps (SATCOM) Modes

Item	274Mbps Downlink		45Mbps Downlink		Units	Comments
	X	Ku	X	Ku		
Frequency	7.4	11.8	7.4	11.8	GHz	
Transmitter Power	2.9	3.4	0.48	0.55	Watts	
Transmitter Power	4.62	5.31	-3.19	-2.60	dBW	
Transmitter Line Loss	-1	-1	-1	-1	dB	
Transmit Antenna Beamwidth	10	10	10	10	deg	Beamwidth of XPAA
Peak Transmit Antenna Gain	24.30	24.30	24.30	24.30	dBi	
Transmit Antenna Diameter	0.28	0.18	0.28	0.18	m	
Transmit Antenna Pointing Offset	8	8	8	8	deg	Assume 80% error in pointing
Transmit Antenna Pointing Loss	-7.68	-7.68	-7.68	-7.68	dB	
Transmit Antenna Gain (net)	16.62	16.62	16.62	16.62	dBi	
Equiv. Isotropic Radiated Power	20.24	20.93	12.43	13.02	dBw	
Propogation Path Length	895	895	895	895	km	Slant range at max nadir angle = 60
Space Loss	-168.87	-172.92	-168.87	-172.92	dB	
Propagation & Polarization Loss	-0.3	-0.3	-0.3	-0.3	dB	SMAD given value
Receive Antenna Diameter	1.83	1.83	1.83	1.83	m	6 ft MIST antenna
Peak Receive Antenna Gain (net)	40.45	44.50	40.45	44.50	dBi	
Receive Antenna Beamwidth	1.55	0.97	1.55	0.97	deg	
Receive Antenna Pointing Error	0.2	0.2	0.2	0.2	deg	
Receive Antenna Pointing Loss	-0.20	-0.51	-0.20	-0.51	dB	
Receive Antenna Gain	40.25	43.99	40.25	43.99	dBi	
System Noise Temperature	135	135	135	135	K	SMAD Table 13-10
Data Rate	2.74E+08	2.74E+08	4.50E+07	4.50E+07	bps	
Eb/N0	14.04	14.12	14.07	14.05	dB	
C/N Density	98.42	98.49	90.61	90.58	dB-HZ	
Bit Error Rate	1.00E-08	1.00E-08	1.00E-08	1.00E-08	-	
Required Eb/N0	12	12	12	12	dB	Required for OQPSK at 10^-8 BER
Implementation Loss	-2	-2	-2	-2	dB	
Margin	0.04	0.12	0.07	0.05	dB	

The highest power requirement based on this configuration is 3.4 W at the longest slant range. As the satellite travels further into view, the power requirement will decrease. The power requirements determined for the uplink in the preliminary analysis show that a simple semi-directional fixed antenna will provide sufficient gain to close the uplink.

5.2.1.11 Specify the Concept of Operations (CONOPS)

The Communications Architectures defined in the requirements analysis have unique concepts of operation. The CONOPS for the communications repeater and store

and forward architectures is defined here, while the CONOPS for the ISR Payload Data Link architecture will be defined in the ISR Payload section.

5.2.1.11.1 Communications Repeater CONOPS

Under the constraints of the orbital parameters determined as an integral part of the design, providing continuous coverage over the scenario op area will require a constellation of satellites. The elevation angle at which the data link can be successfully closed is based on the antenna maximum steerable angle for the two phased array antennas identified for this application. The XPAA antenna provides the greatest steerable angle of 60 degrees off nadir. This translates to an elevation angle of 22 degrees, which gives a communications window of just under four minutes. Allowing for 30 seconds to initialize the link means cutting the window down to about three minutes for a continuous hand off from satellites to satellite (4min – 30 sec Sat 1 init – 30 Sat 2 init). At the 400 km altitude, the orbital period is approximately 92 minutes, meaning the constellation would require at least 31 satellites to provide continuous coverage.

Assuming that such a constellation could be rapidly launched at a cost that corresponded with the demand, in field surface terminals could use the system to achieve high data rate links (up to 45 Mbps). In the context of this scenario and the cost and time constraints, this is not found to be a technically feasible concept.

5.2.1.11.2 Store and Forward CONOPS

A far more achievable role for LEO tactical satellites is found in the store and forward architecture. Asynchronous communications can be achieved with as little as a single satellite. The satellite would pass over the op area once every 92 minutes, accepting uplinks of new data while down-linking stored data in full duplex. The primary implementations would include:

a. Autonomous unmanned vehicles loitering would upload data for delivery back to the GIG and asynchronous commands would be sent out from the AUVs mission control.

b. Deployed sensors such as DADS would pass along recorded data for delivery back to mission control centers.

c. In field command posts or possibly even man portable terminals would send text, voice, image, or video messages up the chain while simultaneously receiving updated orders, intelligence, imagery, etc.

The time between reception and delivery would be minimized by employing at least two tactical satellites in opposing (one prograde, one retrograde) orbits. In this way the satellite with an eastward ground track could deliver messages quickly within theatre to recipients located east of the sender, and vise versa.

5.2.1.12 Specify Optimal Technology Candidates

Communications Repeater / Store and Forward Configuration

The L3 T-Series Model U equipment provides more than sufficient data rates at extremely low weight and cost that would be capable of supporting both the Communications Repeater and Store and Forward configurations of the TacSat Communications Payload Architecture. The use of the Ku frequency band and full duplex support provide an effective path to small, mobile terminals for LDR or MDR voice/data communications. The CDL compliance makes it interoperable with the MIST surface terminal as well.

ISR Payload Downlink Configuration

The L3 ABIT equipment was used in the TacSat-2 program for very good reason. It is the lightest link equipment that is both CDL compliant and supports data rates up to 274 Mbps. This meets the required data rate to downlink the ISR payload imagery in real-time given the orbital selection and system CONOPS. This payload provides the flexibility to utilize bandwidth in the X or Ku band.

5.2.1.13 Specify Additional Development Requirements

Both architecture implementations would require the modification of existing airborne systems to ensure reliability in the space environment. The many lessons

learned during the TacSat-2 CDL development program could be leveraged to mitigate risk and expedite the process.

TacSat-2 CDL Lessons Learned [Dewey RG, Bishop J 2005]

1) The MMA uses a native MIL-STD-1553 bus, which was not available on TacSat-2 Integrated Avionics Unit, but should be considered in the selection of the IAU for a final Tactical Satellite System.
2) Steering the antenna beam is done blindly due to no status information coming back from the control interface. Currently relies on calculating the angles based on the location of the ground terminal. For mobile applications this will have to be enhanced.
3) Software modifications were required in the MMA to account for the higher Doppler shift experienced with LEO satellites versus airborne platforms. The original range of 0-40 KHz was far below the expected range as high as 250 KHz with a 5 KHz maximum rate of change.
4) The COMSEC implemented in the ABIT MMA was designed for single sortie airborne missions and only holds one key. Final designs will require a modification of the KG-135 device to handle multiple keys.

5.2.2 ISR Payload Architecture

In order to limit the scope of this study to the topics of greatest significance, Intelligence Surveillance and Reconnaissance (ISR) efforts will be limited to imagery (IMINT) with a small discussion of signals intelligence (SIGINT). Acoustic intelligence (ACINT) will be supported through TacSat communication relay capabilities. Measurement and Signature Intelligence (MASINT) as well as other potential ISR uses will not be discussed.

The derived mission requirements did not cover SIGINT however this team feels that if a viable TacSat solution is developed, a SIGINT package could be a simple and inexpensive addition. A brief discussion in provided below. The derived mission

requirements for imagery that drive the presented payload concept dealt mostly with spectral and spatial resolution, image size and the field of view.

In keeping with the larger TacSat concept of providing a low cost and responsive solution, the primary physical payload constraints were mass and power budget. Simplicity also plays a role in keeping costs down.

5.2.2.1 SIGINT

SIGINT is comprised of COMINT and ELINT and involves "listening" to various bands of electromagnetic energy and extracting usable information for further analysis. COMINT refers to intelligence obtained from clear and covered voice transmissions and from the indications of transmissions known as communications externals. ELINT refers to intelligence gathered from interception of other than voice transmissions: telemetry (TELINT), radar (sometimes called RADINT), and other sources of electromagnetic emanations.

The resources required to provide a tactical SIGINT capability on a TacSat should be comparatively small. Covering the entire spectrum from a TacSat is not feasible so a narrower selection of frequencies must be targeted for interception. Using a system such as the sub-satellite ferret on some of the Key Hole satellites would keep size, weight, power, and costs low. Very little unclassified information is available about sub-satellite SIGINT ferrets but they were used with some success prior to 1990. Current solid state receiver technology should be able to provide an affordable solution. A passive wide band antenna/receiver could be added to an imagery bird or a communications relay bird and utilize the same storage and downlink capability already provided. The increase in weight and required power would be relatively small. For this study, the team derived a total mass for the satellite of approximately 450 kg and a small receive-only suit could add 2-4% total mass which is acceptable at this stage of concept exploration.

Since the satellites are in LEO, loiter time over a desired target will be very short and infrequent. Short loiter times still support detection and classification of signals but will not support analysis of complete communications. For this reason, a LEO SIGINT solution would be used primarily for ELINT and communications externals. The

intercepted data would be stored on board until such time as the bird was in view of its ground station. Aside from compression, no other post-interception processing would be performed by the space segment. Again, this is to keep costs low and utilize existing ground capabilities. A small price would be paid in terms of the amount of raw data being down linked but this is offset by the reduction in complexity weight and power required for on board processing.

As an alternative, a HEO TacSat could provide the temporal resolution to enable good COMINT but the additional costs incurred by HEO are not desirable for this program.

5.2.2.2 Imagery

The choices available for imagery payload are varied. From infrared to visible light, active or passive microwave, film or electro-optic detector, framing, cross-track scanning, and along-track scanning; each has its own capabilities and limitations. Roughly using the steps outlined in SMAD 3rd ed. (Larson, 2005), the abbreviated process for choosing an imagery payload is as follows:

1) Select payload objectives.
2) Conduct subject trades.
3) Develop payload operations concept.
4) Determine required payload capability.
5) Identify candidate payloads.
6) Estimate candidate payload characteristics.
7) Evaluate candidates and select a baseline.

5.2.2.2.1 Select Payload Objectives

The imagery payload objectives from section 3 are to provide imagery in a useful format that shows enemy movement and positions, friendly movement and positions, camouflaged equipment, terrain, contaminated areas, and obstacles. This statement encompasses a wide variety of information requirements that can be met by specific types

of imagery technology. This will greatly reduce the field of viable payload candidates as well as allow for trade space when balancing performance with cost. The derived performance requirements for spatial resolution listed in section 3 are 2 meter threshold and 1 meter objective for pan chromatic and a revisit rate of 2 hours threshold and 1 hour objective.

5.2.2.2.2 Conduct Subject Trades

The SMAD definition of subject is basically objects of interest for the imagery payload. There are a few subjects listed in the objective statement: moving and stationary personnel, moving and stationary equipment, facilities, and terrain to various degrees. As a subject trade to keep costs low, TacSat's imagery capabilities will be limited to covering a single type of subject that can be supported by a single imagery payload. For this TacSat imagery variant, the team chose to examine the subject type that would provide the most general benefit to the tactical commander. From a tactical perspective, imagery of unit activity would provide the greatest benefit. This drives the resolution and revisit rate requirements as stated in section 3. From a subject trade perspective, this high resolution limits the ability to provide wide area terrain imagery due to the limited field of view of higher resolution systems at lower altitudes. Furthermore the available unclassified COTS systems that provide resolution in the 1-2 m range are panchromatic, visible spectrum solutions. Technology and cost constraints render infrared, multi-spectral, and hyper-spectral solutions non- feasible and these systems will be eliminated from the subject trade space. This reduces the choice of subjects by eliminating the camouflage subjects that could be detected by infrared systems as well as eliminating the contaminated areas that could be detected with multi-spectral and hyper-spectral systems.

5.2.2.2.3 Develop Payload Operations Concept

The operating concept for the payload is closely tied to the total system CONOP developed in section 3.6. From the tactical commander's request for information through tasking, collection and dissemination, the payload design needs to support these basic functions. The ideal CONOP would encompass an ability for the tactical commander to send instantaneous requests to the TacSat, affect an immediate adjustment to the orbit to

provide the requested target coverage on the same or subsequent pass, collect imagery and relay the imagery in real-time to the tactical commander. A CONOP of this nature would require extensive reliance on existing national communications capabilities for transmitting the data to and from the TacSat. Ideally, if TacSat is considered feasible for full rate production, it should be developed spirally and in parallel with emerging communications capabilities such as Mobile User Objective System (MUOS) and the Joint Tactical Radio System (JTRS) waveform. In this manner, TacSat would be able to take advantage of MUOS for reach-back and tactical units would not need different radios to relay data over TacSat. It would be fully integrated into the Global Information Grid (GIG) and support FORCEnet concepts. In this initial CONOP, requests will be passed to the VMOC for tasking and data will be returned via CDL.

The CONOPS for up-linking commands to the payload will be to use current Air Force infrastructure, direct control from CDL/MIST command posts, and through the use of VMOC. The CONOPS for down-linking imagery data is to transmit at up to 274 Mbps directly to a CDL/MIST command post or transmit compressed imagery data to existing constellations such as TDRS. The requirements for data rate are illustrated in Figure 5-12. Given a one meter pixel size, and 11 to 12 bits per pixel (to support high resolution black and white), a target altitude of four hundred kilometers, and a swath width of eleven kilometers, TacSat will record data at a rate of between 928 and 1012 Mbps. This data rate needs to be compressed at a 4:1 ratio to reduce the output data rate to below the 274 Mbps limit of the CDL. (Figure 5-12)

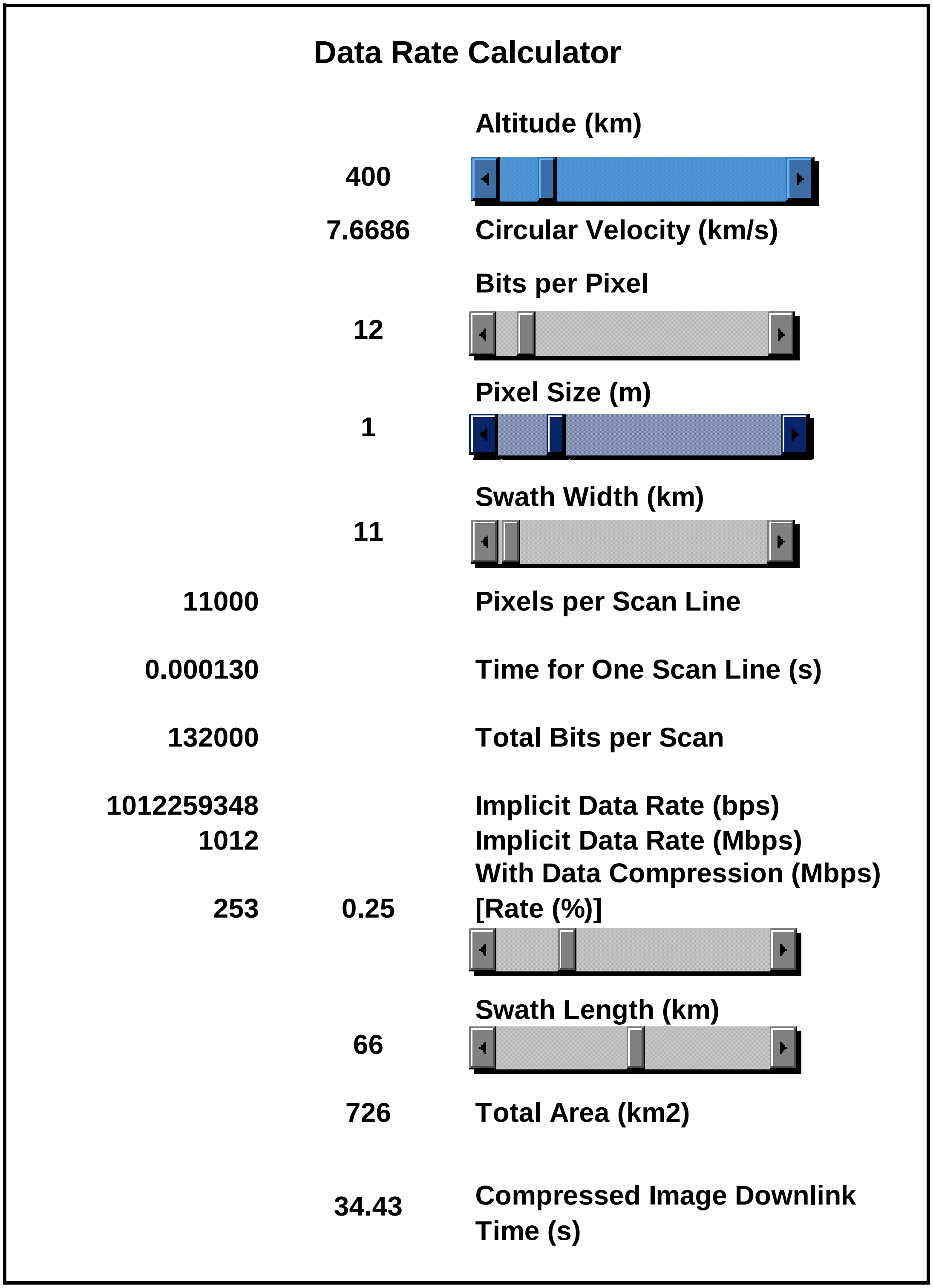


Figure 5-12. Data Rate Calculator (Active excel model)

The goal for TacSat is to transmit data in real time to a CDL/MIST command post in theater. Given an altitude of 400 km the maximum time TacSat will be in view of the command post for downlink transmission is between 4.03 and 10.17 minutes depending on elevation if the ground station is along the ground track (Table 5-18).

Table 5-18. Time in View [Larson W, Wertz J 1999]

MAXIMUM TIME IN VIEW (minutes)				
	Degrees of elevation off horizon from ground station (degrees)			
Altitude (km)	**0**	**5**	**10**	**20**
300	8.67	6.50	4.95	3.10
350	9.44	7.22	5.59	3.57
400	10.17	7.91	6.21	4.03
450	10.88	8.57	6.80	4.49
500	11.55	9.21	7.38	4.93
550	12.21	9.83	7.95	5.37
600	12.86	10.43	8.50	5.81
650	13.48	11.02	9.04	6.24
700	14.10	11.60	9.58	6.66
750	14.71	12.17	10.10	7.08
800	15.30	12.74	10.62	7.50

In consideration of rough terrain a constraint of 20^0 was set and the maximum time was about 4.03 minutes. This time can be further reduced depending on the relative location of the ground station to the area being imaged so planning the location of the ground station is important. The worst case scenario is that TacSat would be in range to downlink for about 90 seconds (30 degree elevation for half the arc). However, at 1 meter pixel size, 12 bits per pixel, and an 11 meter swath, TacSat needs to collect imagery at about at 1012 Mbps and downlink compressed data at about 253 Mbps. Therefore, an 11 km x 24 km section of imagery can be down-linked in about 13 seconds. The largest sections of imagery TacSat would be required to image in this scenario are 11 km x 66 km which would take about 35 seconds to downlink. Depending on ground track TacSat may be in position to image as many as four areas of interest per pass for a total (maximum) downlink time of about 2 minutes. The combined time of 2:20 minutes can be accomplished within the allowed overhead time (time in view) for this scenario. Positioning the ground station for any scenario is important.

The collection portion of the CONOP relies on the target being accessible by the sensor. This can be achieved by adjusting the orbit of the satellite, pointing the entire satellite, pointing a gimbaled sensor within the fixed satellite, or using a pivoting mirror to redirect the path of the sensor's FOV. Table 5-19 discusses some of the advantages and disadvantages .

Table 5-19. Pointing Options

Method	Advantages	Disadvantages
Orbit adjustment	Reduced spatial distortion of off-nadir imagery. Larger total coverage area available.	High cost for propulsion system and fuel in terms of weight and complexity. Longer response time.
Satellite pointing	Less expensive and quicker than orbit adjustment.	Spatial distortion off nadir. Higher inertial forces required than mirror pointing.
Sensor pointing	Less expensive and quicker than orbit adjustment.	Spatial distortion off nadir. Potentially larger satellite required to accommodate physical sweep area of sensor within the bus. Higher inertial forces required than mirror pointing.
Mirror pointing	Simplest, low mass, low cost. Requirements to rotate a small mirror will be less than to rotate sensor or satellite.	Spatial distortion off nadir.

Using the mirror would provide the same general capability as other pointing methods without going to the extreme of adjusting the entire orbit of a satellite. A maximum slew angle of 31^0 will provide the necessary coverage to see all points in between the ground traces of the two consecutive satellites in the constellation chosen in section 4.3 for any altitude selected between 400 km and 550 km.

5.2.2.2.4 Determine Required Payload Capability

With a well defined subject and a goal of providing general applicability at low cost, an imager in the visible (380-780 nm) to near-IR (750-1400 nm) spectrum is dictated. The longer wavelengths will provide better atmospheric transmittance and approaching near-IR wavelengths may help penetrate smoke, foliage, and camouflage. A low cost, panchromatic system with a silicon detector element will provide visible and some near-IR capability (400-900 nm) and require less cooling than other types of elements. [Olsen, 2005]

This wavelength capability must be traded against the other parameters to gain the required resolution within cost constraints. As a general rule of thumb, the cost of an imager is proportional to the aperture diameter (*D*) which is directly proportional to the wavelength (λ) by $D = \frac{2.44\, fQ}{d}\lambda$ (SMAD, '05). As mentioned above, aperture diameters between 0.2 m and 0.5 m should be affordable based on existing systems. Of note, cost can then also be shown to be proportional to the focal length (*f*) and image quality (*Q*) while inversely proportional to the size of the detector element (*d*).

Wavelength also affects resolution by $R = \frac{1.22h}{D}\lambda$ [Wertz J, Van Allen R 2006], so again the desire is to trade for smaller wavelength for better (smaller) resolution. As a baseline, the wavelength parameter constraints will be set to a minimum of 400 nm and a maximum of 1000 nm which closely coincides with silicon's effective range. Figure 5-13 shows the relationship between resolution and wavelength for altitudes of 400 km and 450 km over a range of aperture diameters. Of note, one meter resolution in the visible spectrum is obtainable at both altitudes with an aperture diameter of 0.5 m.

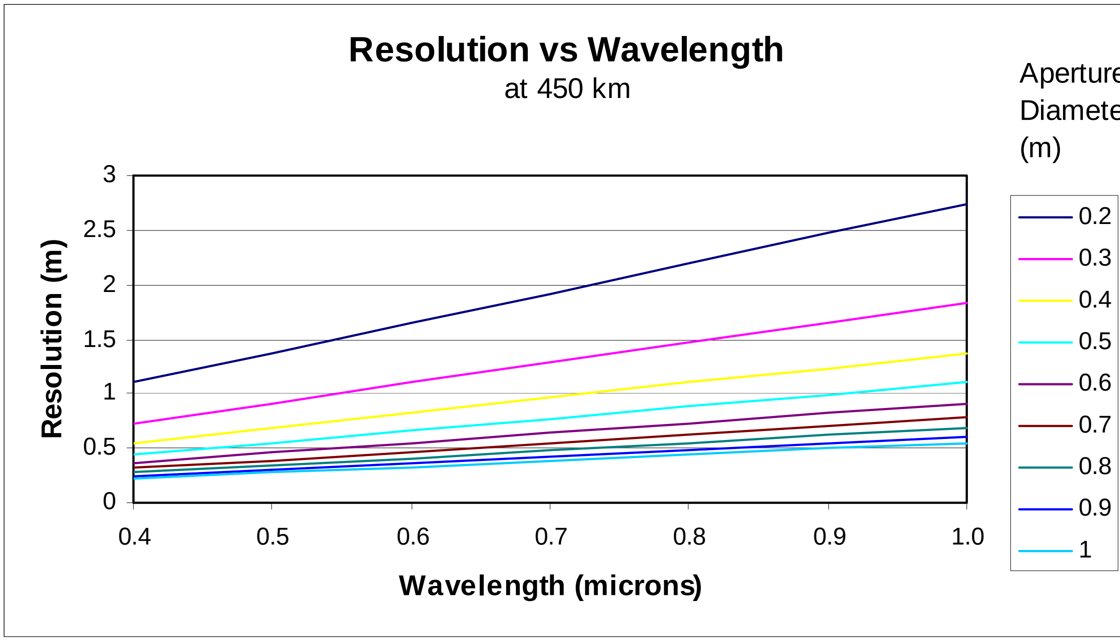


Figure 5-13. Resolution vs. Wavelength

Focal length also directly affects the size of the payload and hence satellite size, weight, cost… From the formula $\frac{1}{f}=\frac{1}{i}+\frac{1}{o}$ where f is focal length and i and o distance to image and distance to object respectively from the primary optics, $f \approx i$ for very large relative values of o. [Olsen, 2005]

As mentioned earlier, the imagery payload cost is closely related to aperture size. Using the equation $R=\frac{1.22h\lambda}{D}$ the Table 5-20 shows resolution capabilities for a range of aperture diameters at a mean visible spectrum wavelength of 0.50 microns. It includes a factor (0.15) for mirror distortions and other imperfections. At 0.5 m aperture diameter, the payload can achieve better than required resolution up to an altitude of 500 km. (Figure 5-14)

Table 5-20. GSD as a function of mirror diameter and altitude

Predicted GSD 30 degrees off nadir													
	Mirror diameter (meters)												
	TopSat				Orbview			Quickbird		Ikonos			
		Actual 30 degree off nadir				Actual 45 degree off-nadir			Actual 30 degree off nadir		Actual 30 degree off nadir		
Altitude	0.20	0.20	0.30	0.40	0.45	0.45	0.50	0.60	0.60	0.70	0.70	1.00	2.40
200	0.85		0.56	0.42	0.38		0.34	0.28		0.24		0.17	0.07
250	1.06		0.70	0.53	0.47		0.42	0.35		0.30		0.21	0.09
300	1.27		0.85	0.63	0.56		0.51	0.42		0.36		0.25	0.11
350	1.48		0.99	0.74	0.66		0.59	0.49		0.42		0.30	0.12
400	1.69		1.13	0.85	0.75		0.68	0.56		0.48		0.34	0.14
450	1.90		1.27	0.95	0.85		0.76	0.63	0.66	0.54		0.38	0.16
500	2.11		1.41	1.06	0.94	1.00	0.85	0.70		0.60		0.42	0.18
550	2.32		1.55	1.16	1.03		0.93	0.77		0.66		0.46	0.19
600	2.54	2.80	1.69	1.27	1.13		1.01	0.85		0.72		0.51	0.21
650	2.75		1.83	1.37	1.22		1.10	0.92		0.78		0.55	0.23
700	2.96		1.97	1.48	1.31		1.18	0.99		0.85	0.82	0.59	0.25
750	3.17		2.11	1.58	1.41		1.27	1.06		0.91		0.63	0.26
800	3.38		2.25	1.69	1.50		1.35	1.13		0.97		0.68	0.28

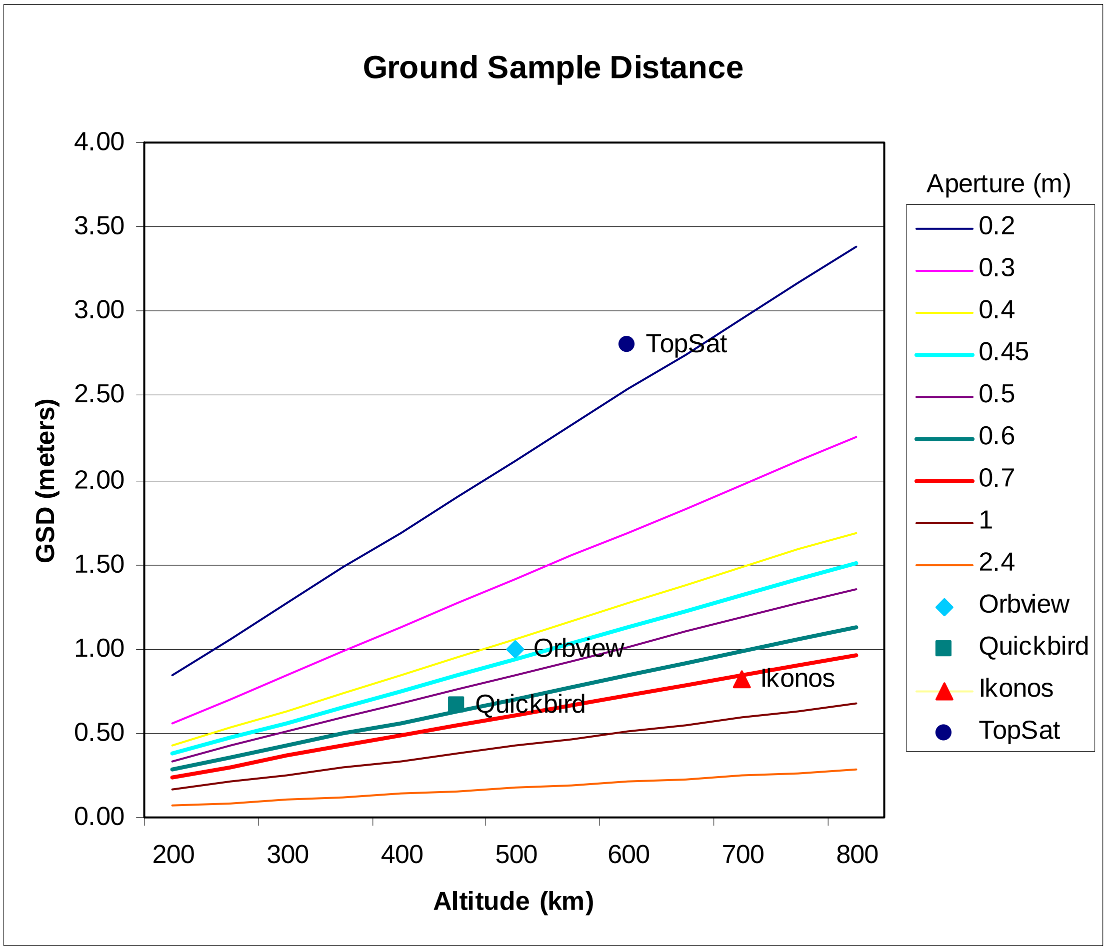


Figure 5-14. Altitude vs. GSD at 0.50 μ for various altitudes (Based on X = 1.22 hλ/D*0.15)

The width of the instantaneous field of view of the imager will depend on the number of detector elements in the linear array and the pixel resolution. With a one meter pixel resolution, the imager should produce images roughly as wide in meters as the number of elements in the array with the appropriate optics. Anticipated capabilities should be from roughly 10 km to 20 km of image width.

5.2.2.2.5 Identify Candidate Payloads and Estimate Characteristics

Many unclassified commercial of the shelf solutions were researched. Almost all were linear arrays of charge coupled devices. Most were off-axis tri-mirror anastigmatic cameras; the physical configuration of which helps reduce overall length of the required

bus while still achieving an effective focal length. The Table 5-21 is a compilation of available data of commercial products whose capabilities are considered to be high resolution. The information found allowed the team to arrive at an understanding of what was feasible and what could be expected from industry.

Table 5-21. Commercial EO parameters [eoPortal 2006]

	Weight: (kg) Satellite/ (Imager)	Orbit (km)	Ground sampling: (m)	Swath width (km)	X-track pointing: (°)	Spectral band (μ)	Pixel size (μ)	Pixel FOV (°)
ElOp EROS A	250(42)	500	1.9	14	45	0.5 - 0.9		
ElOp EROS B	290	500	0.7	14		0.5 - 0.9		
ElOp EROS C	<350	600	0.9	11		0.5 - 0.9		
ElOp MSC (KompSat-2)	800	685	1.0	15X15	56	0.5 - 0.9		
TOPSAT	120/(32)	600	2.5	25			7	
IRS-1D			5.8	63-70		0.5 - 0.75	7	7E-06
IRS-P5			2.5	27-30		0.5 - 0.85	7	
OrbView-3	300/(66)	470	1.0	8	50	0.45 - 0.9		
OrbView-5		684	0.41	15.2	60	0.45 - 0.9		
BHRC 60 (Quickbird)	(296)	400-900	0.5 - 1.25	14-34				
Kodak Model 1000	(88)	600	0.88	12.2		0.45 - 0.9	12	
Kodak OSA (IKONOS)	(171)	700	1.0	11-13	30	0.45 - 0.9	12	
AVNIR-2			2.5	35	40	0.52 - 0.77		
CBERS-4		778	5.0	60	32	0.51 - 0.75		
RazakSAT		685	1.0	20		0.51 - 0.73		
Syers	(180)	300	1.0	6-10	30			

	# Pixels	Lines/ sec	Camera FOV: (°)	Aperture: (m)	Focal Length: (m)	Sampling depth: (bits)	Datalink rate (Mbps)	Power peak: (W)
ElOp EROS A	2x7490	750	1.5	0.3	3.45	11	70	300
ElOp EROS B			1.5	0.5	5	10	280	
ElOp EROS C						10	455	
ElOp MSC (KompSat-2)	15000	7100				10	320	
TOPSAT			1.2x.35	0.2	1.68			
IRS-1D	3*4096				0.9748	6		
IRS-P5	12288				1.945	10		
OrbView-3		2*2500		0.45			150	625
OrbView-5						11		
BHRC 60 (Quickbird)				0.6		11	320	792
Kodak Model 1000	13816	6500	1.19x.75	0.448	8	11		315
Kodak OSA (IKONOS)	13500	6500		0.7	10	11		350
AVNIR-2								
CBERS-4						8	140	
RazakSAT						8		
Syers				0.28	2.8	10	<274	200

5.2.2.2.6 Evaluate Candidates and Select a Baseline

In evaluating the available systems above, efforts were focused on achieving 1.0 meter resolution or better with moderate mass and small aperture measurements as discussed in the payload requirements section. Number of bits per pixel was also considered. While a lower number corresponds to a smaller downlink, much detail can be lost if the number is too low. According to the online Optical Microscopy Primer, humans can only distinguish about 50 discrete shades of gray. This corresponds to 6 to 7 bits per pixel. This number should be bumped up to 8 bits per pixel to avoid producing noticeable steps between gray levels for normal imaging. However, for high resolution imaging where analysts often magnify the image greatly, a dynamic range of 11 to 12 bits is necessary. This produces 2048 to 4096 grayscale levels, allowing the analyst the ability to pick objects out of shadows when digitally adjusting the contrast. [Optical Micro, 2006]

Israel's ElOp provided a viable panchromatic candidate for the EROS-B. EROS-C's panchromatic imager should be similar to B's. Orbview 3 also looks promising with an aperture size within the desired range. Orbview 4 had the same panchromatic sensor as 3 but failed to achieve orbit. Orbview 5, while boasting good numbers will most likely be too expensive for TacSat due to anticipated aperture size. The Kodak offering for IKONOS also has a large aperture, but the Model 1000 seems to have good resolution at smaller aperture size. Though the initial bit rate calculation looks large, Kodak has a proprietary compression algorithm that reduces the bits/pixel from 11 to 2.5 producing a data rate of ~225 Mbps. The Goodrich Syers-2 camera currently used on the U2 platform as well as its successor the DB-110 currently used on tactical aircraft are being looked at for possible modifications to make them viable satellite payloads. Increasing the orbit though will increase the anticipated resolution beyond the objective requirements.

The Kodak Model 1000 is a good baseline candidate as it meets all objective requirements and its digital processing unit can receive input via a standard 1553 data bus. The DPU runs the compression algorithm and then provides the data to an onboard storage unit or data downlink. [Optical Micro, 2006]

5.3 BUS OPTIONS

Section 5.0 outlined common rules of thumb to get first approximations for the spacecraft's key budgets for power, mass, and volume. This section takes the inputs from the payloads analysis, the orbits and constellation analysis, and mission operations sections to perform a more detailed analysis of the spacecraft. This analysis consists of a Microsoft Excel workbook with a series of spreadsheets for the various subsystems of the spacecraft bus. These spreadsheets are linked to each other and changes in fundamental assumptions will propagate through the spreadsheet. The key user inputs are satellite lifetime, the altitude of the orbit, and the mass and power required for the payload. This input access a look-up table that then populates many key variables of the model.

The subsystems analyzed were:

- Propulsion
- Attitude Determination and Control
- Guidance and Navigation
- Communications
- Command and Data Handling
- Thermal
- Power
- Structures and Mechanisms

This Excel model is a powerful systems engineering tool and can be used to conduct analysis of alternatives studies for various configurations of a possible Tactical Satellite or can be used to see how changes in fundamental assumptions affect results. The results presented here are the best effort at achieving a satellite with the maximum tactical utility and the minimum cost. The modeling for each subsystem is described below.

5.3.1 Propulsion

The inputs for the propulsion subsystem analysis are the:

- Satellite life in years
- Spacecraft Dry Mass
- Specific impulse for the selected propellant
- Density of the selected propellant
- Number of thrusters

A monopropellant based system that uses twelve thrusters is recommended. Twelve thrusters provides control about all three axes and insures that torques about any axis are applied as pure couples. [Brown P 169] This should have enough specific impulse to meet the needs of a variety of TacSat missions but is based on simple, low cost, and proven technology. The monopropellant selected for this analysis is Hydrazine. It is stable under most storage conditions, has good handling properties, and clean decomposition. In addition a blow down fuel feed system using either a metal or rubber diaphragm would seem to offer simplicity and low cost.

Given these inputs the first step in characterizing the propulsion system was to develop a delta V budget to describe the required satellite maneuvering. Because TacSatS will use low earth orbits (LEO) they will have to use a significant amount of propellant to make up for drag. To meet the mission needs a constellation is required so station keeping will be required. In the Philippine Sea scenario the selected orbit will require North South station keeping. Another fundamental requirement is to de-orbit the satellite when the mission is through. This is required by international law. Values for Orbit correction, and North South Station Keeping were taken from SMAD table 17-1 and reflect typical values. The value for Drag Makeup was taken from the Earth Satellite Parameters Table in the back of SMAD. Here the worst case value for ballistic coefficient and solar cycle was used.

Once the Delta V budget was generated a propellant budget was developed. The delta V requirement was translated into a propellant requirement by using the rocket equation to solve for required propellant as a function of the dry mass of the spacecraft,

the required delta V and the specific impulse provided by the propellant. An additional 10 percent was added to this value to account for attitude control and another 25% was added to this total to provide a safety margin. Finally, 2% of this total was added on to account for residual propellant. These percentages were based on common rules of thumb. [Larson W, Wertz J 1999 p 713]

The propellant budget is the entering argument into determining propulsion system in terms of mass, volume and power. The propellant mass was determined in the previous step and its volume was easily determined by its density. Based on rules of thumb given by SMAD the mass of the tank was determined to be 10% of the mass for the propellant. SMAD also provided typical values for the mass and power requirements for thrusters and their accompanying lines and fittings. The summary of results for the propulsion system is shown in Table 5-22.

Table 5-22. Summary of propulsion system

Component	Mass (kg)	Volume (m3)	Power (w)
Propellant	126.66	0.13	
Pressurant	2.67	0.06	
Tank	12.67	0.21	
Thrusters	4.80	0.00	60
Lines and Fittings	7.00	0.00	
Total	153.80	0.21	60

5.3.2 Attitude Determination and Control

This section describes the mechanisms for determining the space crafts attitude and the mechanisms for controlling its attitude so the payload sensors and antennas are pointed at the appropriate target on the earth's surface. The methodology for conducting this analysis was as follows. First, the general types of attitude sensor and control mechanisms were selected based on TacSat requirements. Next, the disturbance torqueses due to various external factors were estimated. Then taking the worst of these torques as an estimate of the requirement for the control authority of the attitude control actuators the requirements in terms of momentum and magnetic torque were determined.

This in turn allowed us to estimate the mass and power requirement for these actuators. Finally the mass and power for typical attitude sensors were added to complete the subsystem preliminary power and mass budgets.

TacSat payloads such as communications systems and SIGINT systems have more liberal requirements than those for imagery payloads for pointing accuracy and platform stability. Based on this the imagery payload was used to determine the pointing accuracy and stability requirements for the satellite. Assuming a required stability of around 0.1 degree, and the requirement to minimize cost and complexity, momentum wheels were selected as the method for maintaining three-axis stability. Eventually the wheels reach a maximum and there needs to be some way to dump the built up momentum. It was decided to use magnetic “torquers” for this purpose. While meeting the stability requirements for the TacSat system this arrangement also has a long pedigree and is relatively straight forward and low in cost. To determine attitude and meet the requirements for pointing accuracy it was decided to use a combination of a sun sensor and an earth horizon sensor. This provides both accuracy and some degree of redundancy. Redundancy for the actuators is provided by using four wheels in a tetrahedron configuration. Any one momentum wheel can be lost and the system will still provide three-axis stability.

In estimating the external torques applied to the space craft the key inputs are the altitude and the required stability. In addition there are several key inputs based on the configuration of the satellite itself. These include the difference between the center of mass and the center of solar pressure and the difference between the center of mass and the aerodynamic center of pressure. These two factors provide the lever arm for determining the torque applied by solar radiation and the atmosphere respectively. In addition for determining gravity gradient torques it is necessary to estimate the spacecrafts difference in moment of inertia between its Z axis and the smaller of its remaining axes. An octagonal structure was used based on the assumption that an octagonal structure closely approximates a cylinder estimates for surface area, and moments of inertia were created using a cylindrical model. Values for length and diameter were created based on the dimensions of the shroud for the Pegasus launch vehicle. Given the masses resulting from this analysis Pegasus is an unlikely choice of

launch vehicle but its shroud size made an acceptable entering argument. Like all these models further iterations can be done as more accurate information becomes available.

Internal torques due to sloshing fluids, uncertainty in the center of gravity, thruster misalignment, mismatch of thruster outputs, flexing structural members and others factors were neglected. For TacSat it was assumed that the external torques applied by environmental factors will dominate. Using the simplified equations for estimating worst case disturbance torques provided in Table 11-9A of SMAD the effect on the spacecraft was estimated for Gravity gradient effects, solar radiation effects, magnetic field effects, and aerodynamic effects. Because TacSat is intended for low earth orbit it is expected that gravity, magnetic and aerodynamic effects would predominate and this indeed was found to be the case. The first orbit selected was at 350 km. Because this was a very low orbit aerodynamic effects were quite pronounced. The model was run conducting various system trades and at an altitude of 400 km much better results were obtained. In addition to environmental effects the torque needed to slew the spacecraft 15 degrees in ten minutes was examined. This might be necessary for picking out specific targets to image.

The worst case torque was found to be due to aerodynamic effects and was approximately 1.73e-4 Newton meters. For a spacecraft this is a sizable torque. Armed with this information the required momentum storage in the momentum wheels was determined using the simplified equations from SMAD Table 11-12. The magnetic dipole required to dump this torque once the momentum wheels were saturated was calculated using simplified design equations from the same table. A margin of five times was added to the value for the magnetic torque. Finally based on this information mass and power were estimated based on existing systems that provide similar amounts of momentum storage and magnetic dipole moments. The results are summarized in Table 5-23.

Table 5-23. Component Mass and Power

Component	Scaling Factor based on values in SMAD	Mass (Kg)	Power (w)	Volume
Momentum Wheel	3.43	17.18	51.54	2.15E-03
Electromagnets	3.38	6.76	27	8.45E-02
Sun Sensor		1	0.25	1.25E-02
Horizon Sensor		5	10	6.25E-02
Total		29.937	88.819	1.62E-01

5.3.3 Guidance and Navigation

Guidance and Navigation is important for the TacSat mission for a number of reasons. Since a constellation will be necessary to provide the needed coverage a station keeping function will be important. In addition because of the low orbits used, there will be only a short time when the satellite is overhead so it is important to have sensors and antennas oriented quickly. This implies accurate knowledge of the satellites location.

Traditionally guidance and navigation functions have been carried out on the ground. Ground observations are made to determine the satellites current position and velocity. Positional accuracy of several kilometers is typical. Algorithms are then used to propagate this orbital information forward to predict the satellites position at future times. Recently, however, there has been several development efforts aimed at automating the guidance and navigation functions. While most of these are in the proposed phase, GPS has been used operationally and the Microcosm Autonomous Navigation System (MANS) has been flight tested. Adopting an automated approach to guidance and navigation would not only support TacSat’s flexible, tactically oriented concept of operation, it would also provide significant cost savings. Additional development cost might be incurred up front but these would be more than offset by the savings in ground operations costs. In contrast to ground processing of Navigational data, because of its real time nature onboard automated processing is particularly suited towards real time targeting of the sensors and antennas on their subjects below.

GPS provides a low cost but accurate (15m-100m) means of determining position. It also has the added advantage of providing precise timing information. This information facilitates communications and geo-location functions. GPS suffers the disadvantage, however, of being potentially vulnerable to enemy disruption. For this reason GPS is recommended as the primary source of positional data and using MANS or a MANS like system as a back up. The MANS itself provides accurate (100m-400m) position information. It also provides algorithms for determining data on the ground look point and the sun's direction. The ground look point data could be particularly useful for supporting the TacSat CONOPS by insuring that the satellite is pointing at its subject as it passes overhead. The MANS relies on Earth, Moon, and Sun positional data for its calculations. The Earth and Sun data are already available from the sensors for the Attitude Determination and Control (AD&C) subsystem so achieving a MANS capability relies only on the addition of a Moon sensor.

A Guidance and Navigation system based on GPS and MANS and leveraging the Sun and Earth sensors already used for Attitude Determination and Control would have mass, power, and volume profiles as depicted in Table 5-24.

Table 5-24. Mass, Power and Volume Profiles

Item	Mass (kg)	Power (W)	Volume (cu. m.)
Additional Sensor for Moon	4	7	
GPS	4	12	0.0047
Total	**8**	**19**	**0.0047**

5.3.4 Telemetry, Tracking, and Command (TT&C)

The TT&C system outlined here supports the command and Telemetry functions of the bus. In order to maintain the payload flexibility desired of a TacSat standard bus it was decided that the various types of payloads would be required to supply their own data down link.

Sizing the TT&C down-link begins with assumptions regarding data rates and frequencies. Based on these assumptions a high level link budget was constructed. The required carrier to noise ratio and link margin was estimated which provided the basis for

solving the EIRP. Backing out antenna gain and connector and cable losses gave us a value for the transmitted power. The approximate power efficiency of a transmitter of a general type was based on the design curves given in SMAD figure 13-15. The power requirements for the rest of the system were taken from the typical S band system described in SMAD table 10-23. The mass for all components of the system was taken from this same table.

There are some design decisions and assumptions that are implicit in this model and need to be explicitly acknowledged here. First the decision was made to use an S band down link. This choice was made because there are many such systems with extensive space pedigrees in use today. S band communications is supported at most existing ground stations including the Air Force Satellite Control Network (AFSCN). In fact the assumed receiver G/T and downlink data rates were based on this network. A moderate antenna gain of 1.5 dB was assumed. While a dish with some directivity is envisioned it is desired to keep the foot print wide so as to minimize the pointing and tracking requirements. In order to determine slant range to the vehicle a factor of 1.5 was applied to the spacecraft altitude. Because of the moderate transmit power requirements solid state components were selected as the basis of the design. The results are shown in Table 5-25.

Table 5-25. Mass, Power, Volume Component

Component	Mass (kg)	Power (W)	Volume (cu. m)
Antenna	2	0	
Diplexer	1.2	0	
Receiver	1.8	4	
Transmitter	2	4.7	
Total	7	8.7	0.09

5.3.5 Command and Data Handling

Required mass, power, and volume of the command and data handling (C&DH) subsystem were estimated by making a list of the required functions that needed to be handled by this system. Armed with this data and an understanding of complexity, complexity, the mass, power, and volume were estimated based on historical data.

The functions handled by the C&DH subsystem are:

- Command processing
    - Orbit Correction
    - Station keeping
    - Payload instructions
- Telemetry Processing
    - Fuel level
    - Temperature
    - Attitude
    - Navigation

The actual communications portion of this system is handled in the TT&C subsystem section above. The focus was on the processor that interprets commands and formats telemetry as well as the sensors, interfaces, cabling, and switching equipment that collects the telemetry information and distributes the commands.

In order to keep TacSat flexible and low cost, telemetry, command, guidance, and navigation functions were combined within a single processor. With the simple low cost functionality anticipated for the TacSat bus and the capabilities of modern processors this should be feasible. B rated military specification (milspec) parts were recommended. as opposed to space qualified parts since they are adequate for the low orbits and relatively short mission duration anticipated for TacSat.

A separate data link for the reconnaissance payloads is recommended as the bus is expected to accommodate a variety of payloads. This will require separate processors

and communications gear for the payload portion of the spacecraft. Cross-links between this equipment and the bus could provide some redundancy.

The guidelines for sizing a C&DH subsystem provided by SMAD require outlining the functions and configuration of the system as done above. Then based on this description it is categorized based on its complexity and whether or not it combines telemetry with command and data handling into one processor. The Complexity level is based on fundamental requirements coupled with system requirements such as parts quality and whether or not a distributed computing approach is used. The design choices made include a combined architecture but TacSat system is still in the typical complexity range. This is the middle ground between simple and complex.

This data and the parametric estimation data given in Table 11-29 of SMAD permit estimates of the mass, power and volume requirements for the TacSat bus. Taking the midpoint of the ranges given in Table 5-26 results in the following estimations:

Table 5-26. TacSat Bus Volume

Mass (kg)	Power (W)	Volume (cubic meters)
5.5	16	0.0075

5.3.6 Power

Array Size

Key factors in determining the capabilities of the proposed spacecraft, its reliability, and its cost include power generation, storage, conditioning, and control. A model was developed to determine the required size and mass of the solar array, batteries, and the power distribution, control, and conditioning equipment.

The model for the solar array and batteries is based on data for power requirements as well as data for expected performance of solar electric cells and data for the environment they are expected to operate in. The entering argument is simply how much power is required. This power must be supplied both during daylight and during orbital periods of eclipse. Compensation for the different efficiencies of the distribution

system during times of charging (daylight) and during times of battery operation (eclipse) is required. The equation below provides the value for the power that must be provided by the solar arrays.

$$Psa = [(PeTe/Xe) + (PdTd/Xd)]/Td$$

Pe is the power required during eclipse and is equal to Pd the power required during daylight. Te is the expected time of eclipse in a single orbit and Td is the expected time of daylight in a single orbit. Finally Xe and Xd are the energy transfer efficiencies for the times of eclipse and daylight.

Once the power output from the solar panel was determined it was necessary to select a material for the solar cells and determine how much power they can produce per square meter. The cheapest most easily used material is silicon. In an effort to keep TacSat simple and inexpensive it was initially assumed that silicon is the material to be used. Silicon has an efficiency of 0.148. From this, the expected solar radiation of 1367 Watts per meter squared and results in an estimated output power Po of 202 Watts per meter squared.

There are several factors that degrade the performance of a solar array and these must be taken into account. The most important are inefficiencies in design and assembly, temperature effects, and shadowing of cells by other parts of the spacecraft. Using nominal values form SMAD an inherent degradation factor was determined to be Id = 0.77. In addition some compensation must be included for the pointing angle of the sun. If the sun is not perpendicular to the array at all times then the maximum amount of energy will not be produced. This factor is given by Cos(A), where A s the angle between the solar cells and the line to the sun. All of these factors are combined to provide the arrays required power output per unit area at the beginning of its life. This is given by the equation below

$$Pbol = (Po)(Id)(Cos(A))$$

Finally compensation must be made for array performance as it degrades throughout its life due to environmental conditions. This degradation is primarily due to thermal cycling, micrometeorite strikes, and from material out gassing during the

duration of the space mission. The life time degradation is a function of the typical degradation per year and the desired satellite lifetime. The degradation factor Ld is given by the equation below.

Ld = (1 – degradation/year)^satellite life in years

This in turn provides the expected array output per unit area at the end of the satellites life, Peol.

Peol = (Pbol)(Ld)

Now it is possible to calculate the array size Asa. It is the required power from the array calculated in the first step divided by the expected output per square meter of array at the end of its life.

Asa = Psa/Peol

This model was instantiated in spreadsheet form and can be iterated for various power requirements, solar cell materials, or orbital parameters. Using the rule of thumb that an array typically produces 25 W per kg of mass of the array is determined. [Larson W, Wertz J 1999 table 11-33, p 410]

This model assumes that a planar array is used. The alternative would be to use solar panels on the body of the spacecraft. This would provide a simpler, more reliable and less expensive approach. Using this approach, however, imposes an additional penalty because the entire array is not seen by the sun. For spin stabilized spacecraft the arrays would need to be larger by a factor of pi. For three axis stabilized spacecraft with body mounted arrays the arrays must be increased in size by a factor of 4. [Larson W, Wertz J 1999, p 416]

Battery Requirements

The most important factors for battery size are the orbital parameters. The battery must be chosen so that it can supply the required power during times of eclipse. This is given by the required power during eclipse multiplied by the length of the eclipse or PeTe.

In addition it is not practical to completely drain the battery and then completely recharge it every cycle. Some Depth of Discharge (DoD) must be determined. The Depth of discharge has a dramatic effect on battery life. The deeper the discharge, the less cycles the battery can endure. A rule of thumb for NiCd batteries is if there will be less than 1,000 cycles throughout the mission lifetime the batteries can accommodate a DoD of 80%. Conversely for a lifetime of more than 10,000 cycles a DoD of only 30% can be accommodated [Larson W, Wertz J 1999 figure 11-11, p 421]

There is also the question of how many batteries (N) will be used and what their transmission efficiency (n) is for the system. All of these factors taken together provide a required battery capacity in watt hours of

Cr = (PeTe)/(DoD)(N)(n)

The given power required in watt hours, divided by the specific energy density for the selected battery chemistry, equals an estimated mass. For NiCd batteries which have seen extensive use in space and therefore are reliable and inexpensive the specific energy is approximately 27 Watt hours per kilogram. Lithium Ion cells have recently seen a great deal of application and provide energy densities on the order of 75 Watt hours per kilogram. [Larson W, Wertz J 1999. Table 11-39, p 420] It may be worth the extra cost to use these batteries in TacSat, especially if significant savings in mass and volume are gained. Finally one should determine whether redundancy is necessary. If so then the number of batteries should be doubled.

Power Distribution Control and Conditioning

The initial budgeted mass for the power distribution, control, and conditioning is based on rules of thumb from SMAD P. 334. While this is sufficient for this study it is worth making a few observations and recommendations. The devices used to distribute the power, control the power, condition the power, and provide protection against short circuits all add cost, complexity, and mass to the spacecraft. Based on the desire to keep TacSat simple, reliable, and low in cost the following recommendations are in order:

- Use an unregulated power bus. Because the payloads used with the TacSat spacecraft vary it is not possible to anticipate what their needs will be. It is therefore better to simply have each payload design in its own power conditioning and regulation. This is not so much a savings in cost and mass as it is a shifting of the requirement and the corresponding cost and mass to the payload portion of the spacecraft design.

- A shunt regulator should be used to regulate the output of the solar array. This is the simplest, most reliable way to achieve this requirement and has the added advantage of using less mass.

- Parallel charging should be employed. While this shortens the life of the batteries it provides significant savings in mass and complexity. This approach is appropriate for a TacSat that anticipates a relatively short spacecraft lifetime but also requires simple inexpensive spacecraft.

The sizing of the power subsystem is given in Table 5-27.

Table 5-27. Power Subsystem Size

Item	Mass (kg)	Power	Volume
Array	51.3	0	0.0170
Batteries	25.4	0	0.0025
Control and conditioning	33.3	48.1	0.4165
Total	110.0	48.1	0.4362

5.3.7 Structures

The key requirement for the TacSat structures is operational flexibility. (As opposed to structural flexibility.) All the usual concerns about maintaining strength and rigidity while minimizing mass and cost apply. In the case of TacSat, however, the structure must support a variety of payloads rather than just being optimized for one or a few particular ones. This will be particularly difficult with regards to modal analysis.

Of the three types of structural packaging concepts widely employed as outlined by Griffin and French in Space Vehicle design the Skin Panel/Frame type is recommended. The dual sheer plate approach simply does not lend itself to the TacSat CONOPS because it requires custom packaging and cabling of the payload and electronics. While the shelf type does lend itself to this it has poor heat transfer characteristics. The Skin Panel/Frame approach easily accommodates standard black boxes for the electronics and maintains good thermal characteristics. This type of structure consists of a frame with panels attached. Frequently these panels are hinged. The electronic equipment is directly mounted on these panels. This type of structure has the additional advantage of providing easy access. This too is supportive of the TacSat CONOPS.

The FLTSATCOM satellite is an excellent example of this kind of structure and packaging approach. It has some additional characteristics that should also be applied to TacSat. FLTSATCOM has two hexagonal frames with hinged panels for accommodating generic black box electronic packages. The first frame contains the standard bus subsystems and the second frame hosts the payload. In the case of FLTSATCOM the payload was a large communications transponder. In the case of TacSat, however, this second frame could host a variety of payloads and could supply standard mechanical and electrical interfaces. The mechanisms for storing the solar panels for launch and then deploying them when in orbit that was used by FLTSATCOM provides another proven approach that could be incorporated into TacSat. Leveraging a scaled down version of the FLTSATCOM structural design would provided the mission flexibility needed by TacSat while minimizing costs by incorporating proven designs.

The appropriate size for the structures and mechanisms for TacSat is compared by analogy to FLTSATCOM. To do this the rough estimate of dry mass was calculated for TacSat and divided it by the dry mass of FLTSATCOM to get a scaling factor. The mass for the FLTSATCOM structures was then multiplied by this factor to obtain an estimate for TacSat. The results are shown in Table 5-28.

Table 5-28. Mass for the FLTSATCOM

	Dry mass	Scaling factor	Structures mass (kg)
FLTSATCOM	841		154
TacSat	458	0.544	83.86

This technique of course assumes a linear relationship as large structure is scaled to a smaller one.

Considering that TacSat will be in a LEO rather than GEO orbit some additional rigidity will be required and this will lead to a need for more mass. Another satellite with similar construction but destined for LEO orbit is HEO-B. Table 5-29 summarizes the structural scaling using this satellite. This spacecraft, however, has a massive radar payload that requires considerable support. The final estimate is an average between HEO-B and FLTSATCOM. This results in an estimated structural mass of 64.61 kg. Table 5-30 summarizes other structural data for the satellite. These estimates are based on it fitting within the shroud for a Pegasus launch vehicle.

Table 5-29. Structure Scaling

	Dry mass	Scaling factor	Structures mass (kg)
HEO-B	2868.2		779
TacSat	284.2	0.09908	77.185

Table 5-30. Spacecraft Structural Data

Diameter (m)	1.1		Ix	150.60
Radius (m)	0.55		Iy	150.60
Length (m)	1.8		Iz	75.907
Surface Area (sq. m.)	8.12		Difference	74.694
Volume (cu. m.)	1.71			

5.3.8 Thermal

A detailed thermal analysis is beyond the scope of this study. A top level spacecraft design that is more detailed than this initial systems feasibility analysis would be necessary in order to have the inputs to develop a more detailed analysis. In this section describes a high level approach to how the spacecraft can be thermally managed. This approach can then lead to a rough estimate of the necessary mass and cost for a thermal control system.

The thermal energy that enters the spacecraft from the earth and the sun plus the thermal energy generated internally by the electronics needs to be balanced against thermal energy lost to the deep space environment. Keeping this equation in balance is made more difficult by the fact that thermal energy entering the spacecraft can change considerably as the spacecraft orbits. There can also be a tremendous temperature differential between the sun facing side of the spacecraft and the other sides.

The classic approach to maintaining this thermal balance is to insulate the spacecraft to keep heat in and then use conduction to move internally generated heat to an exterior surface where it can be radiated into the cold of space. Special coatings work to minimize the thermal coefficient of absorption and maximize the thermal coefficient of radiation for a given surface. Variability of heat impinging on a spacecraft during an orbit can be compensated for by using mechanisms like louvers that open and close

depending on how much waste heat must be expended to space. In some circumstances active measures must be taken to maintain a given temperature range. These measures include the use of heating elements and cooling mechanisms such as heat pipes or cryogenic systems.

Passive mechanisms are recommended to support simple, low mass, and low cost approaches. Using the structural configuration outlined above, the mounting panels will serve to draw heat to the skin of the spacecraft with no additional mass or cost. This will requires only the additional mass of the thermal blankets and coatings. This was calculated using an average value of 0.73 kg per square meter for a blanket and assuming the entire space craft was covered. [SMAD table 11-49, p 457]

Most spacecraft have a custom thermal design for the particular spacecraft and orbit. The TacSat mission CONOPS will not support this as TacSat is expected to operate in a variety of orbits with a variety of payloads. A more generic and flexible approach can be adopted by leveraging the approach developed for the structural arrangement. The recommended structural approach outlined above involved using two octagonal sections. The first would be the spacecraft bus and the second would host the various TacSat payloads. This approach allows a relatively straight forward approach to the thermal design of the first section at the expense of shifting complexity into the design of the second module. However, the use of louvers in this section can provide the kind of flexibility needed not only for various orbits, but also for various payloads. Louvers can support up to a 6 times variation in heat transmission in the open to close position. [SMAD, p 442] In addition, they require no power to operate. A louver was added to the system with a mass of 5 kg per square meter. [Derived from SMAD table 11-47A, p 443] The result of this high-level estimate is given in Table 5-31. The table reflects the fact that the analysis model will support numerous thermal control techniques. The initial design approach uses only passive techniques and many of the inputs have been zeroed.

Table 5-31. Initial Design Approach

Thermal Control Item	Mass/Area (kg/sq. m.)	Mass per length (kg/m)	Mass / Unit	Number of Units	Mass	Power/ Unit (W/Unit)	Power (W)	Volume (m cubed)
Thermal Blanket	0.73	N/A	5.92	1	5.92	0	0	0.202
Coatings		N/A	0	1	0	0	0	
Radiator Panels	3.3	N/A	26.78	0	0	0	0	
Louvres	5	N/A	2.25	1	2.25	0	0	0.028
Active heaters	N/A	N/A		0	0	0	0	
Heat Pipes	N/A	0.15	0.165	0	0	0	0	
Control for Active heaters	N/A	N/A	0.2	0	0	2	0	
Total					8.18		0	0.231

While not recommended here there is another approach that may be worth investigating further. The Soviet space program made frequent use of pressurized vessels containing the equipment for the spacecraft bus and payload. This allowed the use of forced convection for thermal transfer. This approach is simple and inexpensive but carries with it the risk of a possible breach in the pressure vessel. TacSat is designed to be an inexpensive spacecraft that makes up in numbers what it may lack in reliability. With this in mind the use of forced convection in a pressure vessel might be a good option.

5.3.9 Conclusions

The summary of the key bus parameters is given in Table 5-32.

Table 5-32. Key Bus Parameters Summary

Subsystem	Mass (kg)	Power (W)	Volume (cu. m)
Propulsion (including propellant)	153.79	60.00	0.214
Attitude Determination and Control (AD&C)	29.93	88.82	0.162
Guidance and Navigation	8.00	19.00	0.005
Communications	7.00	8.75	0.088
Command and Data Handling (C&DH)	5.50	16.00	0.008
Thermal	8.18	0.00	0.232
Power	109.99	48.14	0.436
Structures and Mechanisms	64.61	0.00	0.022
Total	387.02	240.7	1.165

Table 5-33 compares the results in Table 5-32 to the initial estimates.

Table 5-33. Key Bus Parameters Comparison

Bus subsystems	Original Mass (kg)	Original Power (W)	Current Mass (kg)	Current Power (W)	ΔMas s (kg)	% ΔMass (kg)	Δ Power (W)	% ΔPower
Propulsion	18.32	10.00	24.47	60.00	6.14	33.52	50.00	500.00
Attitude Control	32.07	30.00	29.94	88.82	-2.13	-6.64	58.82	196.07
TT&C	27.49	20.00	12.50	24.75	-14.99	-54.52	4.75	23.76
Thermal	9.16	10.00	8.18	0.00	-0.98	-10.72	-10.00	-100.00
Power	96.20	60.00	110.00	48.14	13.80	14.34	-11.86	-19.76
Structure	77.88	0.00	64.61	0.00	-13.26	-17.03	0.00	0.00
Totals	261.12	130.00	249.69	221.71	-11.42	-0.04	91.71	0.71

After attempting to refine estimates based on specific TacSat mission the bus mass has increased by only 4.37 percent. The power, however, has increased by 70 percent. The absolute change in power, however, is 91.7 Watts. Both propulsion and attitude control increased considerably compared to initial estimates. This is due to the fact that the statistical data that the original estimates were based upon do not accurately

reflect the effect of the low orbit on these two subsystems. While these are somewhat rough numbers they should provide good inputs to the cost estimating model.

It should be pointed out that this bus is oversized both structurally and in terms of power for many candidate TacSat payloads. The reason for this is that in order to realize the TacSat vision of a common bus for all payloads the bus must be designed in such a way that it accommodates the most demanding traits of the family of payloads. It must accommodate the structural needs of an imagery payload as well as the power needs of a communications payload. These worst case values were used as fundamental inputs to the bus design model.

This study concluded by reproducing the calculations of Table 5-4 using the updated information from the more detailed analysis. The results are shown in Table 5-34. The boost weight is 17 kg under of the nominal capability of FALCON I.

Table 5-34. Spacecraft Mass Summary

Element	Value (kg)
Payload	75.00
Bus subsystems	
Propulsion	24.47
Attitude Control	29.94
TT&C	12.50
Thermal	8.18
Power	110.00
Structure	64.61
Margin	77.93
Dry mass Total	**402.63**
Propellant	130.40
Loaded Mass	533.03
Kick stage	0.00
Injected mass	533.03
Adapter	20.00
Boost weight	553.03

5.4 LAUNCH VEHICLE OPTIONS

The launch vehicle represents the most critical interface with the spacecraft. [Brown C, 200239] The selection of the launch vehicle occurs early in the process. The critical technical interfaces are the launch mass capability and for the purposes of the study, cost. Table 5-35 outlines the possibilities and capabilities of several launch vehicles:

Table 5-35. Launch Vehicle Options [Larson W, Wertz J 1999 p802]

Launch Vehicles	Max Payload (kg) to LEO	Unit Cost (FY$00M)	Cost per kg to LEO (FY$00K/kg)
Atlas II	6,580	80-90	12.2-13.7
Atlas II A	7,280	85-95	11.7-13.0
Atlas II AS	8,640	100-110	11.6-12.7
Athena 1	800	18	22.5
Athena 2	1,950	26	13.3
Athena 3	3,650	31	8.5
Delta II	5,089	50-55	9.8-10.8
Pegasus XL	460	13	28.3
Titan II	1,905	37	19.4
Taurus	1,400	20-22	14.3-15.7
Falcon 1	570	6.7	11.8

As shown from the table, launch vehicle costs can vary dramatically. The last entry in the table refers to SpaceX's re-usable launch vehicle – Falcon 1. This promises to be a dynamic system that will revolutionize the industry of launch vehicles by providing a low-cost, highly reliable solution to the problem of expensive launches. This promise has yet to be fulfilled at the time of this writing.

6.0 SYSTEM COST ANALYSIS

6.1 COST ESTIMATING METHODS

Several methods for cost estimation range from general to specific: expert opinion, analogy, parametric, engineering, and extrapolation. Expert opinion is simply the judgment of an expert or group of experts upon the final cost of system based upon experience in the field. Analogy is the process of comparing the system with a comparable existing system in the past. Parametric estimation uses a database of systems in the field and creates cost estimating relationships (CERs) that relate the specified parameters of the new system with values calculated from the database. Engineering estimation uses a compilation of estimates from the lowest levels of the Work Breakdown Structure (WBS). Extrapolation is a method that uses cost information from the earlier or previous units of the same system.

To estimate the cost of a new system, the primary methods used are analogy, parametric, and engineering. Figure 6-1 shows the typical amount of use for each of these methods throughout the phases of a project. The analogous method is best used when the new system is very similar to existing systems. The analogous method is quick, inexpensive, and easy to change. However, the analogous method is not very precise and is best used for high system level estimation. [Col. David Matthews, USA Ret.] The parametric method calculates values by creating CERs that are reflective of values determined from a database. The CERs are created by regression analysis on data points. The CER then represents a relationship between cost and some technical parameter(s). Parametric estimation has the advantage of being quick and easily adapted to model changes. The disadvantage of parametric estimation is that the precision is only as good as the database. Parametric estimation also requires the use of the appropriate class of system. Satellites, for instance, have different categories. Large satellite systems such as UFO and DSCS have different cost factors than small scale satellite systems such as a Microsat. Thus, small scale satellite systems must be estimated differently on different databases than large scale systems. This is particularly an issue with TacSat as it has missions and parameters that are very similar to traditional satellites and yet it is

envisioned as being smaller and lighter than these systems. Thus it is difficult to find a good historical base to work with. The engineering estimation method goes through a detailed cost estimation process for each component of the system from the lowest levels of the WBS. This method should be the most reliable – however requires the largest amount of effort. Engineering estimation requires the use of drawings, material costs, make/buy decisions, subcontracting for different components and so forth. This method is not very easily adaptable to model changes and is subject to the accuracy of the WBS as well as the potential of omissions, failed risk assessments, and misinterpretations. This method is not appropriate to a high level feasibility study such as this one.

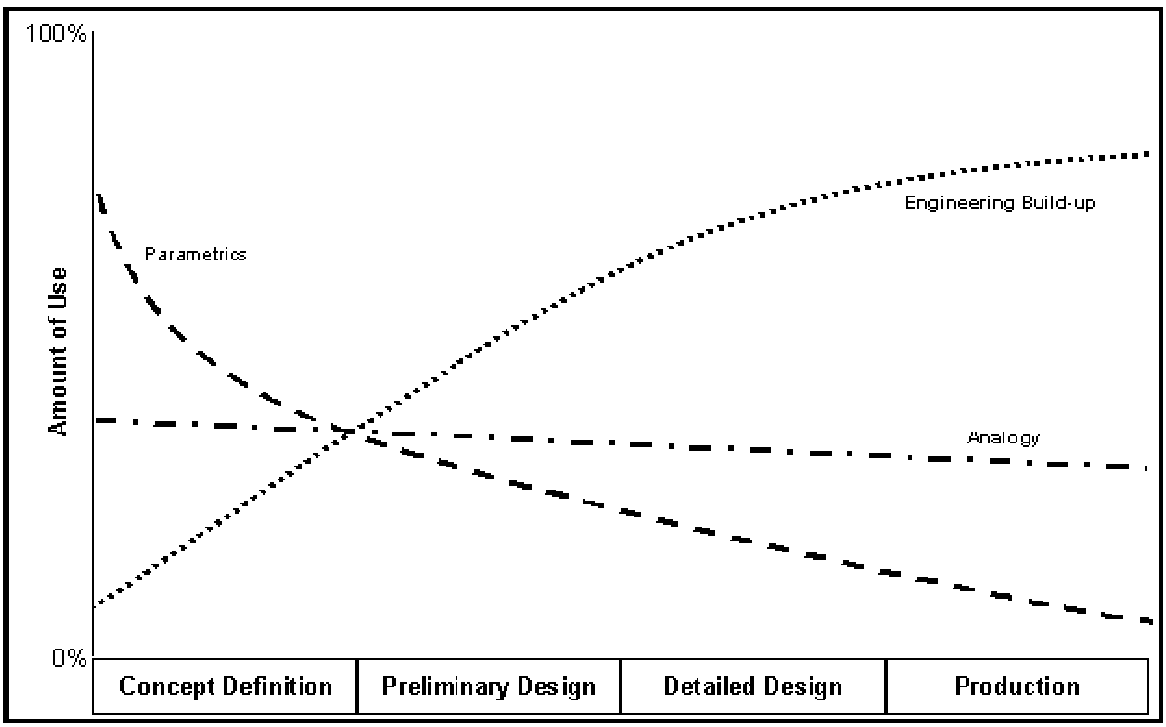


Figure 6-1. Cost-Estimating Methods Usage [SSCM05 User's Manual]

In order to provide an estimate of the complete TacSat system, the following phases are assessed: the space segment (spacecraft and payload), the launch segment (launch vehicle and total launch cost), the ground segment (facilities, equipment/software, and O&M), and the program costs (systems engineering, program management and integration, assembly and test (IA&T)). [Anderson, Timothy P.] In

order to decide on an approach, “the scope of the effort, the detail of technical design definition, the availability and applicability of usable historical costs, and the ability of the cost estimators” must all be evaluated. [SSCM05 User’s Manual, Page 3] A combination of expert opinion, parametric, and analogous estimation methods are utilized to estimate the cost of the TacSat subsystems. The engineering estimation method is not used since it requires the complete “spacecraft design, manufacturing, and procurement to be laid out in great detail.” [SSCM05 User’s Manual, p3]

6.2 APPROACH

6.2.1 Parametric Cost Estimates

The Small Satellite Cost Model (SSCM), developed by the Aerospace Corporation, is a parametric cost model. To assess the complete spacecraft bus, Aerospace used the data from 53 satellite programs to “derive and document CERs for each of the following bus subsystems and associated programmatic and integration costs:

1) Attitude Determination and Control Subsystem (ADCS)
2) Propulsion
3) Power
4) Telemetry, Tracking, & Command (TT&C)/ Command & Data Handling (C&DH)
5) Structure
6) Thermal
7) Integration, Assembly, & Test (IA&T)
8) Program Management (PM)/ Systems Engineering (SE)
9) Launch and Orbital Operations Support (LOOS)

[SSCM05 User’s Manual, p2]

SSCM provides a range of values for each technical parameter since “each CER was generated from a specific dataset and is only intended to be valid within this range”. [SSCM05 User’s Manual, Page 115] If one or more values are outside the range; “the user must decide whether the CER is still applicable”. [SSCM05 User’s Manual, p116] Table 6-1 shows that most TacSat input parameters were within the range of the model’s

requirement. These inputs were based on a satellite bus that could sufficiently support any of the possible payloads. The areas that did not fall within the range of values were: power subsystem mass, propulsion subsystem dry mass, and transmit power. The reason for this is due to the uniqueness of the TacSat common BUS approach. The common BUS is a work horse that must support a variety of payloads. Subsystems such as power and propulsion are oversized to provide flexibility rather than being carefully tailored to a specific payload as is usually done. Conversely the telemetry link for the BUS is undersized due to a very low data rate. This resulted from the assumption that payload data would be down linked using a CDL data link built into the payload section of the spacecraft. The overall mass of the spacecraft is kept low by eliminating complexity and minimizing redundancy wherever possible.

Due to export laws by the U.S. Government, the CERs are not able to be published in this study. For details regarding the CERs used, please contact the Aerospace Corporation.

Table 6-1. Range of Values for SSCM Inputs

Technical Parameter	Range				
	Low	Minimum	Value	Maximum	High
Design Life		6	12	96	
Satellite Wet Mass		113	545.1984	877	
Bus Dry Mass		45	415.8675	674	
Power Subsystem Mass		19.3	109.9971	96	14.6%
BOL Power		56.5	240.7144	2500	
Solar Array Area		0.71	8.769399	14.6	
Structure Subsystem Mass		6.7	64.61276	182.9	
ADCS Subsystem Mass		5.8	29.93785	58.5	
Pointing Knowledge		0.01	0.1	1.5	
Propulsion Subsystem Dry Mass		9	153.7972	118.2	30.1%
C&DH Subsystem Dry Mass		3.25	5.5	31	
Transmit Power	97.5%	1.5	0.037594	5.5	
Thermal Subsystem Mass		0.5	8.180031	21.3	

The Spacecraft/Vehicle Level Cost Model (SVLCM) "is a top-level model derived from the NASA/Air Force Cost Model (NAFCOM) database".[http://www1.jsc.nasa.gov/bu2/SVLCM.html] It provides an estimate of a

scientific instrument's development and production costs based its dry mass. Other CERs exist to reflect payload costs based upon aperture diameter (for optical payloads) or the mass of the subsystem for communications payloads. [Larson W, Wertz J 1999, p796]

6.2.2 Analogous Cost Estimates

Analogous estimation methods will be used for the launch vehicle. The TacSat program intends to "break-the-mold". The use of low-cost launch vehicles is a part of the solution.

6.2.3 Expert Opinion

Expert opinion is used for estimation of the ground segment. Timothy P. Anderson, Senior Engineering Specialist at the Aerospace Corporation provided information regarding the ground segment as well as general rules of thumb and overviews of the cost estimation process.

6.2.4 Cost Drivers

The primary cost driver for the spacecraft bus and communication subsystem is mass. For the purposes of estimation, as the mass increases, the cost proportionally increases as well. Mass is directly related to the cost of the bus subsystems. For the imagery payload, the primary cost driver is aperture diameter. As the diameter increases, the mass increases also, as does the cost.

As the spacecraft bus and payload increase in mass, care must be taken to ensure that the total mass does not exceed the capacity of the launch vehicle. In this case, Falcon 1 has a payload capacity of 570 kg. As mass increases, many factors change, including launch vehicle options and the CERs themselves as the satellite changes from a small, low mass satellite to a medium or heavy mass satellite.

6.3 RESULTS OF COST ESTIMATION

6.3.1 Space Segment

6.3.1.1 Spacecraft Bus

Table 6-2 shows the results generated by SSCM for the spacecraft bus subsystems. It provides estimates, in FY06$, for recurring and non-recurring costs. "Non-recurring costs including all efforts involved with design, drafting, engineering unit IA&T, ground support equipment, and the portion of program management and system engineering costs that can be identified as non-recurring. Recurring costs cover all efforts associated with flight hardware manufacture, IA&T and the portions of program management and system engineering costs that can be identified as recurring". [SSCM05 User's Manual, p13-14]

Table 6-2. SSCM Cost Estimate

	Estimate (FY06$K)				% of	% of
	Non-rec	Rec	Total	Std Error	Sub-level	Sys-level
Spacecraft Bus Subsystems						
ADCS	2,133	1,544	**3,677**	1,199	17.4%	
Propulsion	2,782	2,782	**5,565**	1,786	26.3%	
Power	1,664	1,803	**3,467**	985	16.4%	
TT&C*	1	1	**3**	0	0.0%	
C&DH*	2	1	**3**		0.0%	
Structure	4,405	3,190	**7,595**	1	35.9%	
Thermal	455	373	**828**	3,653	3.9%	
Spacecraft Bus	**11,443**	**9,695**	**21,138**	**4,352**	**100%**	49.1%
IA&T	1,658	3,691	**5,349**	362		12.4%
PM/SE	5,893	5,020	**10,913**	3,994		25.3%
LOOS	0	5,678	**5,678**	2,300		13.2%
S/C Development & First Unit	**18,994**	**24,083**	**43,077**	**6,349**		**100%**

6.3.1.2 Payload Cost Estimates

Key cost estimating relationships for payloads are driven by aperture diameter (m) and communications subsystem mass (kg). Program level costs for RDT&E and Theoretical First Unit (TFU) were computed using Cost Estimating Relationships (CERs) in SMAD, Chapter 20. Table 6-3 shows the RDT&E cost and corresponding CER. Table 6-4 shows overall program level cost estimates for the Payload which were determined using CERs for Estimating Subsystem Theoretical First Unit (TFU) Cost. The validity of the CERs is limited to a range of values, because they were derived from historical data. Using the equations beyond 25% the parameter ranges will compromise its validity [Larson W, Wertz J 1999, p795]

The values for each cost component were derived from previous analysis in this study, and both are within the acceptable input data range of the CER

Table 6-3. Payload Cost Estimate for RDT&E. [Larson W, Wertz J 1999].

Cost Component	Parameter, X (unit)	Input Data Range	RDT&E CER (FY00$K)	Value	Cost (FY00$K)
Visible Light Sensor	Aperture dia. (m)	0.2 – 1.2	356,851 $X^{0.562}$	.4 m	$213228
Communications	Comm. subsystem wt. (kg)	65-395	353.3X	105.363kg	$37224

Table 6-4. Payload Cost Estimate for Theoretical First Unit (TFU) [Larson W, Wertz J 1999]

Cost Component	Parameter, X (unit)	Input Data Range	TFU CER (FY00$K)	Value	Cost (FY00$K)
Visible Light Sensor	Aperture dia. (m)	0.2 – 1.2	51,469 $X^{0.562}$	.4 m	30754
Communications	Comm. subsystem wt. (kg)	65-395	140X	105.363kg	14751

The program level cost includes cost for program management, systems engineering, product assurance, and system evaluation. The allocation of the program level cost to each component is shown on Table 6-5. The cost allocation percentages were provided as part of the analysis in SMAD. [Larson W, Wertz J 1999, p798]

Table 6-5. Allocation of Program Level Cost

	RDT&E			TFU		
Program Level Component	Cost Allocation	Visible Light Sensor ($K)	Communications ($K)	Cost Allocation	Visible Light Sensor ($K)	Communications ($K)
Program Management	20%	42645.6	744.8	30%	9226.2	4425.3
Systems Engineering	40%	85291.2	14889.6	20%	6150.8	2950.2
Product Assurance	20%	42645.6	7444.8	30%	9226.2	4425.3
System Evaluation	20%	42645.6	7444.8	20%	6150.8	2950.2
Program Level Costs	**100%**	**213228**	**37224**	**100%**	**30754**	**14751**

The CERs used for these payloads are based upon large scale satellite systems. Thus the values may be slightly different that those for smaller satellite programs. Another model that estimates payload costs is the Spacecraft/Vehicle Level Cost Model by NASA. [http://www1.jsc.nasa.gov/bu2/SVLCM.html] The input parameters to the model are listed in Table 6-6.

Table 6-6. SVLCM Inputs

Quantity	10
Mass	105 kg
Learning Curve	90%

The output of the model yields the results in Table 6-7.

Table 6-7. SVLCM Payload Summary (FY00 $M)

Development Cost	$21.13
Production Cost	$53.45
Unit Cost	*$ 7.46*
Total	**$ 74.58**

With the SVLCM, the unit price per payload is significantly cheaper. Again, this is an estimate based upon the projected mass of the payload.

6.3.2 Launch Segment

The launch segment includes the cost of the launch vehicle and the launch itself along with orbital operations support (LOOS, Table 6.2) before ownership is given to the operational user. As seen in the launch vehicle table, options vary significantly. The

payload capacity required is determined by the mission need. Depending upon constellation size and the location of orbits, a single launch may be sufficient, or multiple launches may be necessary. "The LOOS is composed of prelaunch planning, trajectory analysis, launch site support, launch-vehicle integration (spacecraft portion), and initial on-orbit operations". [SSCM05 User's Manual, p13] This component was able to be estimated by SSCM05 (Table 6-2).

6.3.3 Ground Segment

Ground segment costs have been estimated by expert opinion to be approximately $1 million per person per year. This individual would work for 8 hours/day. Thus for constant 24 hour monitoring, three (3) individuals would be needed. These figures do not include new facility construction, but rather would utilize existing space in facilities such as the Air Force Satellite Control Network of ground stations.

6.3.4 Program Costs

SSCM includes program costs (Table 6.2). These costs include systems engineering (quality assurance, reliability, requirements activities), program management, data/report generation, and special studies not covered by or associated with specific satellite subsystems.

6.4 COST SENSITIVITY AND RISK ANALYSIS

Based on the report of the Comptroller General of the United States, there are three major causes of cost growth: inflation; requirement changes, and estimating error.

6.4.1 Inflation

Cost estimating for future space vehicle systems often requires planning five to ten years ahead. Estimating costs needs specific attention to the changes in the dollar's purchasing power because future expenditures are sensitive to inflation. Inflation is an

"increase in the overall level of prices over an extended period of time" and loss of purchasing power. [www.mcwdn.org/ECONOMICS/EcoGlossary.html]

Cost projections are made from a particular time and the estimates are sensitive to historical information. Historical cost data from satellites dating from 1970s are used to estimate costs for current programs. Each spacecraft data point used are normalized to year dollars to FY00$ using the Office of Secretary of Defense (OSD) inflation indices. Thus, inflation plays a major role in cost sensitivity and risk analysis.

6.4.2 Requirement Changes

Requirement changes results from a myriad of factors such as program mission changes, technical alterations from design problems, and program redirection. Deviations from program baselines are caused by requirement changes. In addition, such requirement changes tremendously affect program cost, resulting in cost overruns.

Parametric cost modeling is "based on cost estimating relationships (CERs) that make use of product characteristics (such as hardware mass and complexity) to estimate costs and schedules". [http://www1.jsc.nasa.gov/bu2/PCEHHTML/pceh.htm] Therefore, parametric cost modeling reflects historical cost experience and the cost changes within today's program. Thus, future program will benefit from today's programs because of accurate historical data.

The SSCM's cost estimating relationships rely on technical parameters for space vehicles. It is important to use realistic parameters for estimating costs based on historical parameters. The SSCM program generates its cost estimates by using preliminary mass inputs to input into CERs using a database of historical information. One approach is to assume probability distributions based on the mean and range of the historical data. Then one can apply a random selection technique such as the Monte Carlo that will generate a probability distribution for the cost estimate. However, problems can occur when estimating is at the component or subsystem level because available parameter growth data pertains only to the particular component or subsystem. The mass growth data at the subsystem level in a Monte Carlo analysis is independent from mass growth amounts at each subsystem.

Another approach is to treat configuration uncertainty as discrete with each case having its own associated uncertainty. One can address the uncertainty by using worst and best case scenarios for component and subsystems. This will allow for cost range estimating and can be used in the cost distribution. There are a handful of risk analysis tools such the Air Force Systems Command (AFSC) Risk Model or the risk model created by Tecolote Research to alleviate cost growth from requirement changes. One must combine any risk such as schedule risk, technical risk, the risk associated with limitations of the estimating tools, and requirement changes risk to accurately provide risk dollar estimates and their associated confidence levels.

This is in fact one of the key areas where a TacSat approach is expected to have benefits. The goal is a satellite program with simple well known objectives that deliberately does not try to "push the envelope". It is hoped that this will lead to greater requirements stability and a resulting cost savings.

6.4.3 Estimating Error

There are a myriad of errors that occur in cost estimating a space vehicle program. Errors from technological influences, schedule conflicts, management, and other external factors cause cost deviations or overruns.

Standard errors in cost estimating relationships result in an estimated range for each cost estimating relationship. This range can serve as a conservative assessment of the situation. However, the cost range provided does not reflect the cost range for each component or subsystem. Taking Monte Carlo samples from these subsystem distributions, one can derive a distribution for the total. Thus, a more appropriate range may then be inferred for this total distribution and the Monte Carlos sums for subsystem costs based on the given standard errors can help in a more accurate overall cost estimate. (Figure 6-2)

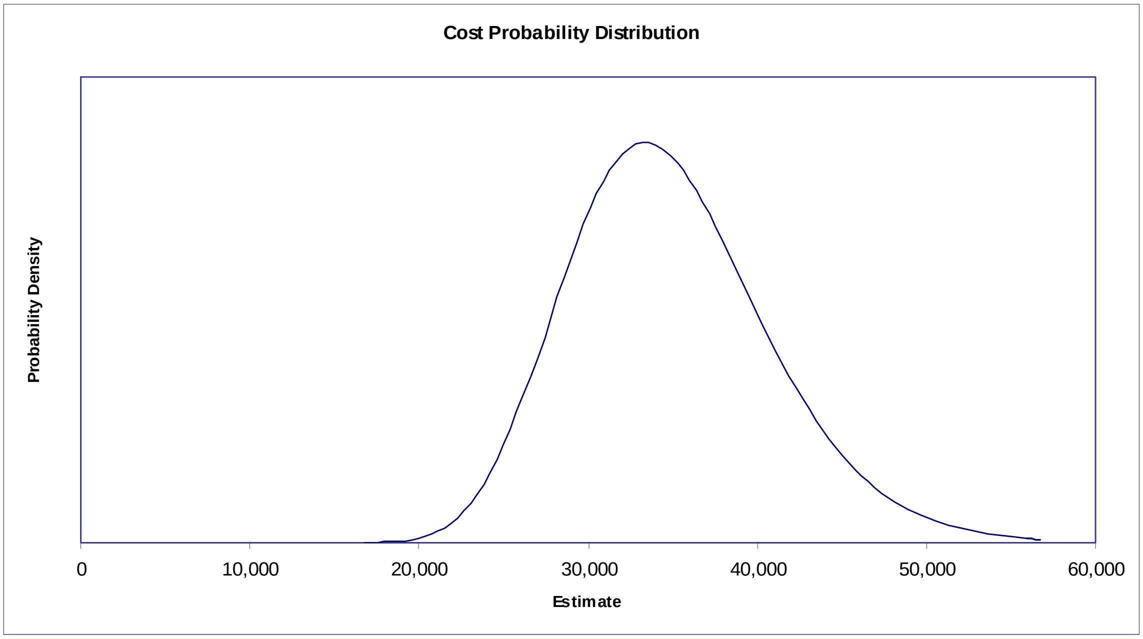


Figure 6-2. SSCM Cost Estimate Probability Distribution

6.5 COST EFFECTIVENESS COMPARISONS

An alternative to TacSat is the Global Hawk RQ-4 Unmanned Aerial Vehicle (UAV). There are advantages and disadvantages associated with either option with regard to cost. The Global Hawk ran approximately $123.2 million in 2004 including development costs and MILCONs (ground stations). [UAV GAO Report, November 2004]

For the purposes of comparison, the following assumptions were made:

- Global Hawks
  - Four (4) Global Hawk RQ-4Bs would be needed as indicated from the gap analysis.
  - Two (2) ground stations would need to be established to support the Global Hawks.
  - Development costs would be amortized across all the fifty-one (51) Global Hawks to be procured (UAV GAO Report, November 2004).

- Figures from the 2004 GAO report would be adjusted to FY$06 dollars.
- Four operators are estimated to be needed for operations, estimated cost $150K/yr/person.
- Three maintenance personnel per ground site are estimated to be required at an estimated cost of $150K/yr/person.
- A C-17 is able to launch three Global Hawks, thus two (2) C-17 flights would be needed at an estimated cost of $300K per flight.

- TacSat
    - Ten (10) satellites are produced in order to amortize the development costs.
    - Two, three, and four satellite constellations would be compared and learning curve is at 90% since a 10 satellite program is assumed. [Larson W, Wertz J 1999, p809]
    - One satellite per launch vehicle (assuming Falcon 1).
    - Ten payloads will be procured and the corresponding development costs will amortized. The payload is a combination of the visible sensor and the CDL data downlink.
    - Ground operations are estimated to be $1M/yr/person for eight hours a day. For 24-hour monitoring, three people will be required for a total cost of $3M/yr. This cost will remain the same whether for two satellites or four satellites. This involves the monitoring reception of data and the satellite after initial launch operations are completed.

As shown in Table 6-8, the Global Hawk operational costs for the Philippine Sea Scenario are approximately $514 million dollars.

Table 6-8. Global Hawk Summary (FY$00 M)

Global Hawk Summary			
	Unit Cost	*Quantity*	*Ext. Cost*
UAV	$ 20.37	4	$ 481.49
Ground Stations	$ 14.00	2	$ 28.00
Operator	$ 0.15	20	$3.00
Maintenance	$ 0.15	6	$ 0.90
C-17 Flight	$ 0.30	2	$ 0.60
Total			**$ 513.99**

The TacSat costs are listed in Tables 6-9 through Table 6-12. Table 6-9 indicates the cost per satellite (using SMAD payload estimates) with the exclusion of ground operations since the cost will be the same regardless of the constellation sizes being considered. The bus, payload, and launch information were taken from above and standardized to FY$00.

Table 6-9. TacSat SMAD Spacecraft and Launch Cost (FY$00 M)

	Unit Cost	*Quantity*	*Ext. Cost*
Satellite Bus	$ 16.80	1	$ 16.80
Satellite Payload	$ 50.86	1	$ 50.86
Launch Vehicle	$ 6.70	1	$ 6.70
Total Per Satellite			**$ 74.36**

Using the SVLCM model, the satellite costs are significantly cheaper as shown in Table 6-10. In this model, the payload portion decreases in expense substantially.

Table 6-10. TacSat SVCLM Spacecraft and Launch Cost (FY$00 M)

	Unit Cost	***Quantity***	***Ext. Cost***
Satellite Bus	$ 16.80	1	$ 16.80
Satellite Payload	$ 7.46	1	$ 7.46
Launch Vehicle	$ 6.70	1	$ 6.70
Total Per Satellite			**$ 30.96**

To evaluate the different constellation sizes, the total cost per satellite was multiplied by the size of the constellation and then added to the ground operations cost. The results for the SMAD version of the satellite are shown in Table 6-11.

Table 6-11. TacSat SMAD Summary (FY$00 M)

	Constellation Size	*Ext. Cost*	*Ground Ops*	*Total*
Constellation A	2	$ 148.72	$ 3.00	$ 151.72
Constellation B	3	$ 223.08	$ 3.00	$ 226.08
Constellation C	4	$ 297.44	$ 3.00	$ 300.44

The results for the SVLCM model are shown in Table 6-12.

Table 6-12. TacSat SVLCM Summary (FY$00 M)

	Constellation Size	*Ext. Cost*	*Ground Ops*	*Total*
Constellation A	2	$ 61.92	$ 3.00	$ 64.92
Constellation B	3	$ 92.89	$ 3.00	$ 95.89
Constellation C	4	$123.85	$ 3.00	$ 126.85

Using the SVLCM model as the principal payload model, the TacSat becomes a very attractive solution. The cost is less than a quarter of a Global Hawk system performing the same mission with four satellites orbiting. In the worst case, using SMAD models for the payload, the cost is still significantly less that the Global Hawk system.

Program costs are often a significant portion of the decision making process. The revised Global Hawk program costs are shown in Figure 6-3.

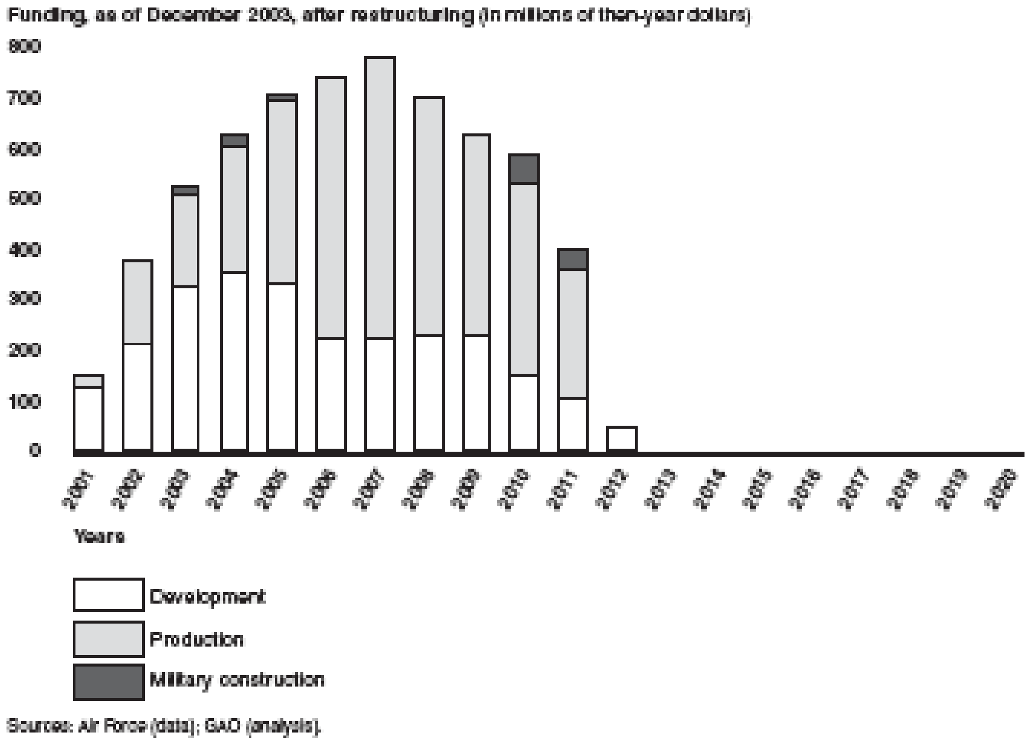


Figure 6-3. Global Hawk's Annual Funding requirements. [UAV GAO Report, 2004]

Program costs were projected on a 20 year program life based upon a 7% discount rate. Using the SVLCM model, the total present cost of a 10 satellite TacSat program would be approximately $217 million (FY$04). The funding profile is shown in Figure 6-4.

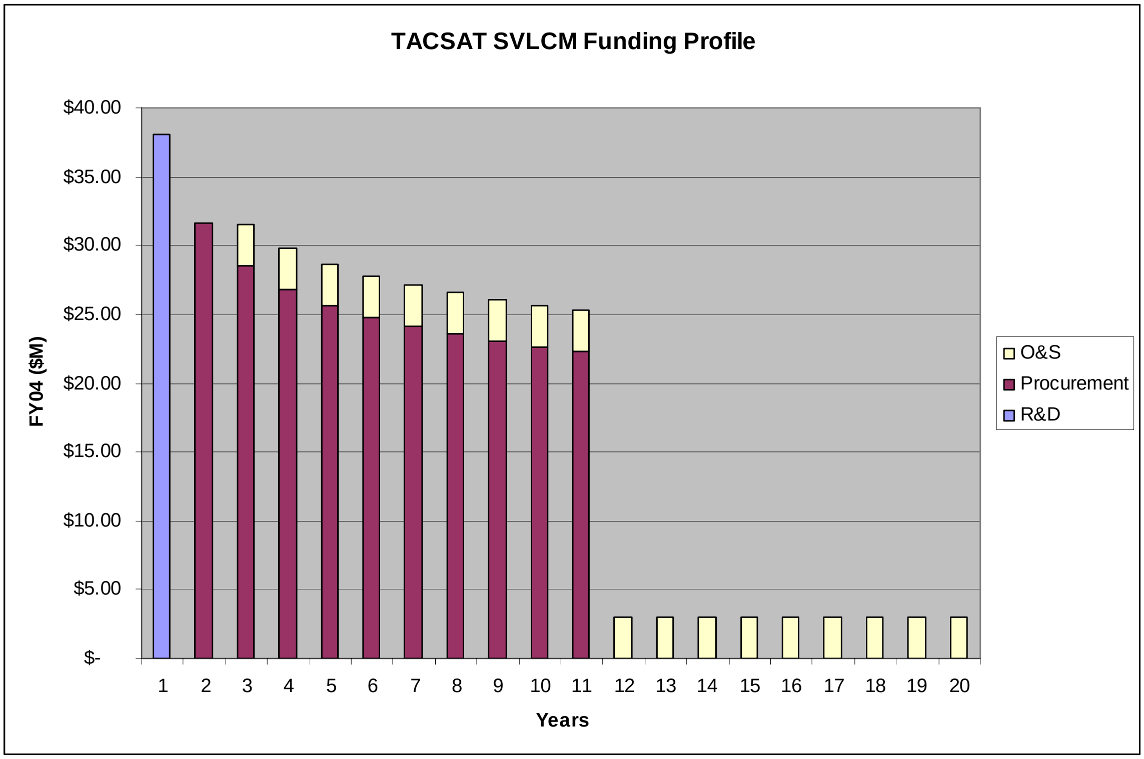


Figure 6-4. SVLCM Funding Profile

Using the SMAD model, the total present value of the 10 satellite TacSat program is approximately $588 million (FY04). The funding profile is shown in Figure 6-5.

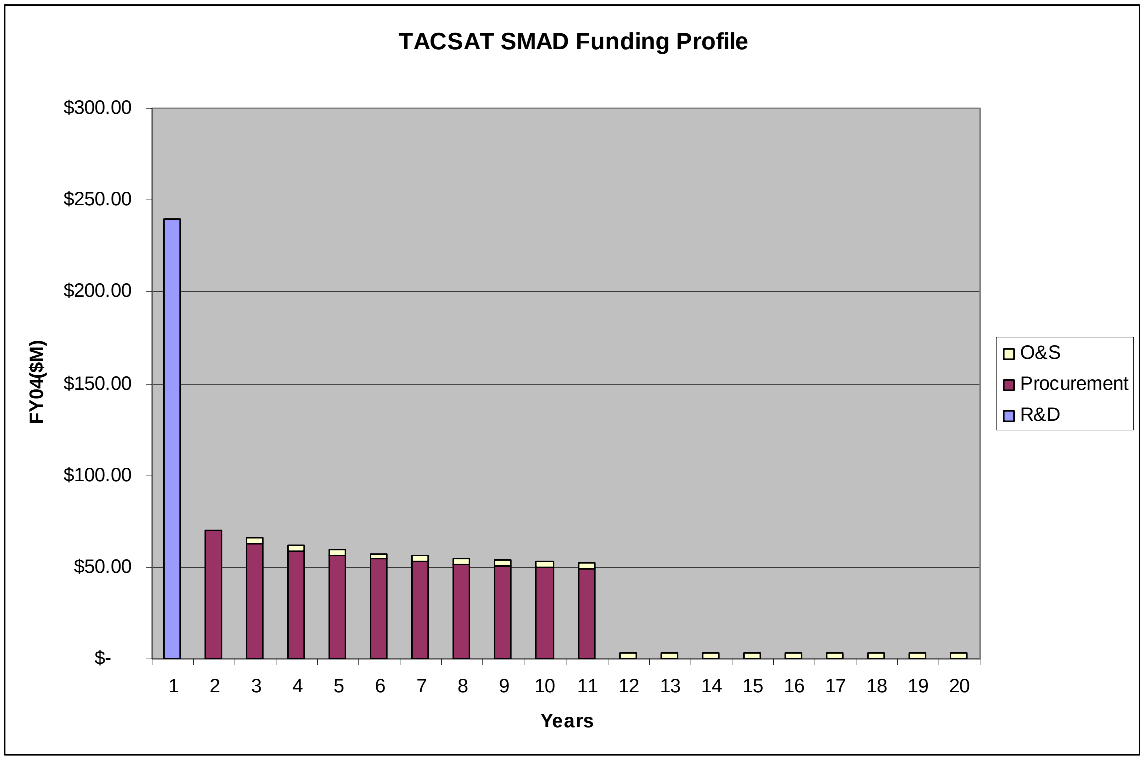


Figure 6-5. SMAD Funding Profile.

All R&D is assumed to be completed in the first year of the program. This will be enabled by using mature technologies to mitigate cost risks and schedule slips. The procurements occur at one per year for the following ten years and production cost decreases by a 90% learning curve. Operation and Maintenance costs are assumed to be the same across the entire life of the program. The very large R&D expenditure in the first year of the SMAD funding profile is due to the very high cost of developing the payloads based upon large-scale satellite CERs. TacSat has a conservative approach of using simple tried and true spacecraft and payload technologies so the R&D expenditures would be lower in these areas and could be used to offset the TacSat unique challenges of a common BUS, responsive timelines, and tactical control of the payload.

6.6 COST CONCLUSIONS

Comparatively, the TacSat program (either the SMAD or SVLCM based models) are significantly less expensive in terms of development and procurement costs per year (Figure 6-6).

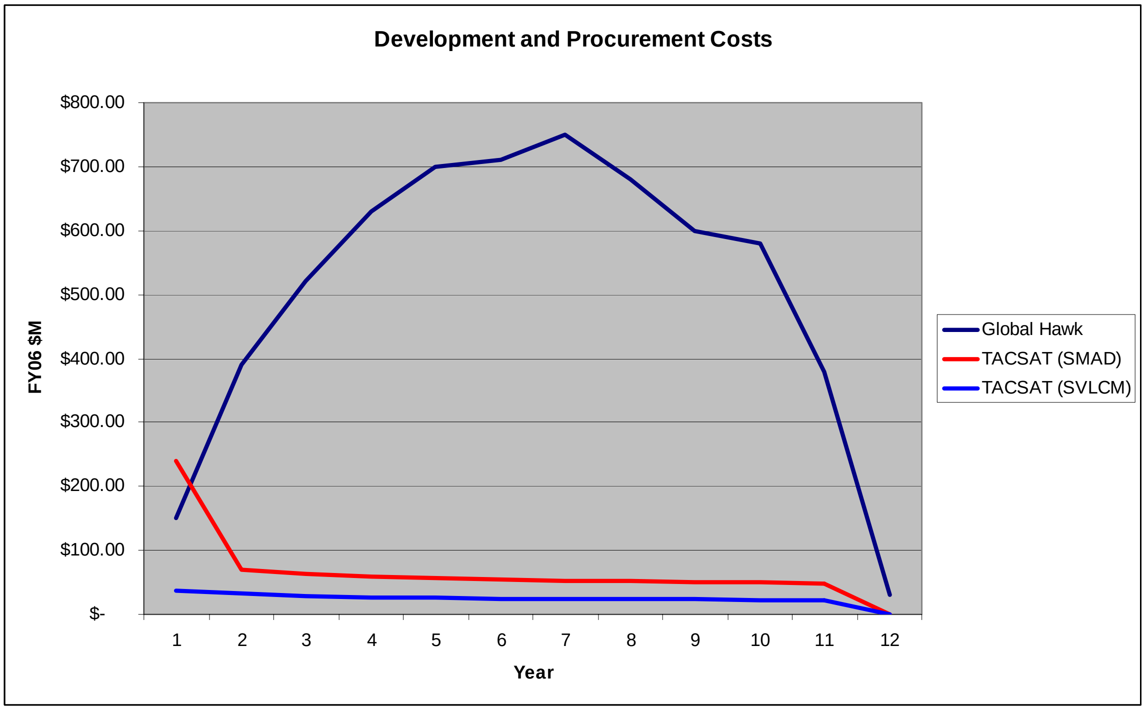


Figure 6-6. Funding Requirements per Year

As a result of comparing the development and procurement costs along with the operations and maintenance cost of each, TacSat is a very viable alternative to the Global Hawk System.

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7.0 CONCLUSIONS

The objective of this project was to examine the feasibility of developing and employing tactically controlled and operationally responsive satellite systems. To ensure relevancy, it was bounded by the requirements and constraints of a realistic mission scenario. The “Philippine Sea Scenario” was selected as the most appropriate for the purposes of this study. Military requirements were obtained from this scenario that drove the requirements for the space mission. These high level mission requirements were then devolved into space system requirements. The “Gap Analysis” compared the mission requirements to current capabilities such as commercial systems, and Global Hawk. The shortfalls identified through the gap analysis were examined as potential capabilities a notional space system might provide.

This high-level space system engineering exercise, based on the SMAD process, was not expected to generate “the” solution for a TacSat system. Rather it was carried out to see if a notional space system could be developed that would meet the requirements and provide military utility. In addition, once armed with such a notional system it was possible to develop some estimates of what it would cost. This analysis does not address issues such as the necessity of TacSat due to vulnerabilities in the national constellation. If such vulnerabilities exist, then a wide range of solutions must be examined and decision makers should not assume TacSat is the only answer.

To meet the scenario requirements, the team analyzed payloads, orbits, and constellation size. These elements drove the development of a common bus. A TacSat system also would need to be supported by ground infrastructure and launch capabilities. In addition, once all subsystems of the TacSat system were analyzed, the Aerospace Corporation’s Small Satellite Cost Model (SSCM) was used to develop a cost estimate.

Technology has advanced greatly since the 1960s, but space costs have not gone down for several reasons. Decision makers continue to push state of the art satellite systems instead of producing more quantities of less capable, but more producible satellites. In this project, the team examined the feasibility of a TacSat system based solely on tactical military utility provided by such a system.

The key results of this exercise are summarized below:

- Requirements Generation. The TacSat system requirements were generated from the Philippines Sea mission scenario. It included stress factors that pushed the limits of such a system including vast distances between ground targets and a requirement to revisit each target hourly. Even with these stress factors, the study showed that a TacSat system could meet those requirements and provide militarily useful imagery, SIGINT, and communications capability. This study also showed that TacSat incurs minimal in theater logistical demands when compared to UAVs.
- UAV Comparison. The same stress factors that make the Philippine Sea scenario a challenge to TacSat also make the scenario a challenge to traditional tactical assets such as Global Hawk. This study pointed out the significant problems the theater commander would have when using a UAV such as Global Hawk to meet scenario mission requirements. Additionally, UAVs impose constraining logistical challenges such as in theater support, airlift, air bases, and staff.
- Constellation Analysis. Analysis indicates a constellation of between two and four satellites in a 400 km orbit with a twenty degree inclination would meet imagery surveillance requirements. A constellation of two satellites provides revisit times of 40 minutes, while a constellation of four satellites provides a revisit time of about 20 minutes.
- Imagery Analysis. The optimal payload for TacSat includes a panchromatic imager with a 0.4 meter optic, and a CDL data link system with an ESA.
- Communications Analysis. The large constellation size required for continuous coverage makes TacSat a non-feasible alternative for general voice and data communications purposes. It is feasible for a store and forward architecture that would support data exfiltration.
- Ground Station Analysis. TacSat requires the VMOC concept for tactical control of the TacSat payload while spacecraft operations and mission control require a globally distributed ground infrastructure. Additional TacSat infrastructure is also required for the launch facilities including pre-staged launch vehicles, payloads, and buses. This TacSat infrastructure has associated costs above and beyond the

costs of the spacecraft and the VMOC infrastructure in theater. These costs can be minimized, however, by using existing Air Force Ground stations and operations facilities.

- Cost Considerations. It is difficult to directly compare satellite systems to UAVs but this study did draw significant conclusions. The procurement costs for a constellation of two tactical satellites is approximately $63 million. It would take four Global Hawks to accomplish the same mission with a price tag of approximately $514 million.

    The natural shelf life of spacecraft and launch vehicles as well as the need to train as we fight requires that there be regular launches of TacSats. This will lead to regular yearly costs associated with the TacSat program but will drive down per unit costs as more spacecraft are produced. This should also encourage more rapid development of and space qualification of new satellite technologies.

Based on the results and observations summarized above this study concludes that it is feasible to develop a tactical satellite system with current technology. Tactical satellites have capabilities, such as providing surveillance over restricted airspace, and covering targets over great geographic distances, that systems such as Global Hawk cannot efficiently provide. Most importantly, the operational costs of these systems vary as a function of time. For short missions, UAVs can provide effective surveillance, while tactical satellites are more cost effective for longer duration missions (1-2 years).

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APPENDIX A. MODELING AND SIMULATION APPROACH

Effectiveness Methodology

TacSat has unlimited orbit and payload design possibilities. To verify potential designs, several iterations of modeling and simulation were performed using Satellite Toolkit (STK) software developed by Analytical Graphics. Launch site, launch windows, and logistics were not determined. The goal of using this software was to provide only orbits, payload, and satellite life cycle verification which align with coverage and access and control issues. Each of these was determined by an STK module or tool.

The effectiveness methodology is as follows.

a) Area of interest (AOI) and timeline. Based on the Philippines Sea Scenario, a futuristic vignette set in the year 2015, several regions in the Philippines and surrounding Indonesia were determined and inserted into the scenario. Below in Figure 1 are the areas of interest developed using STK.

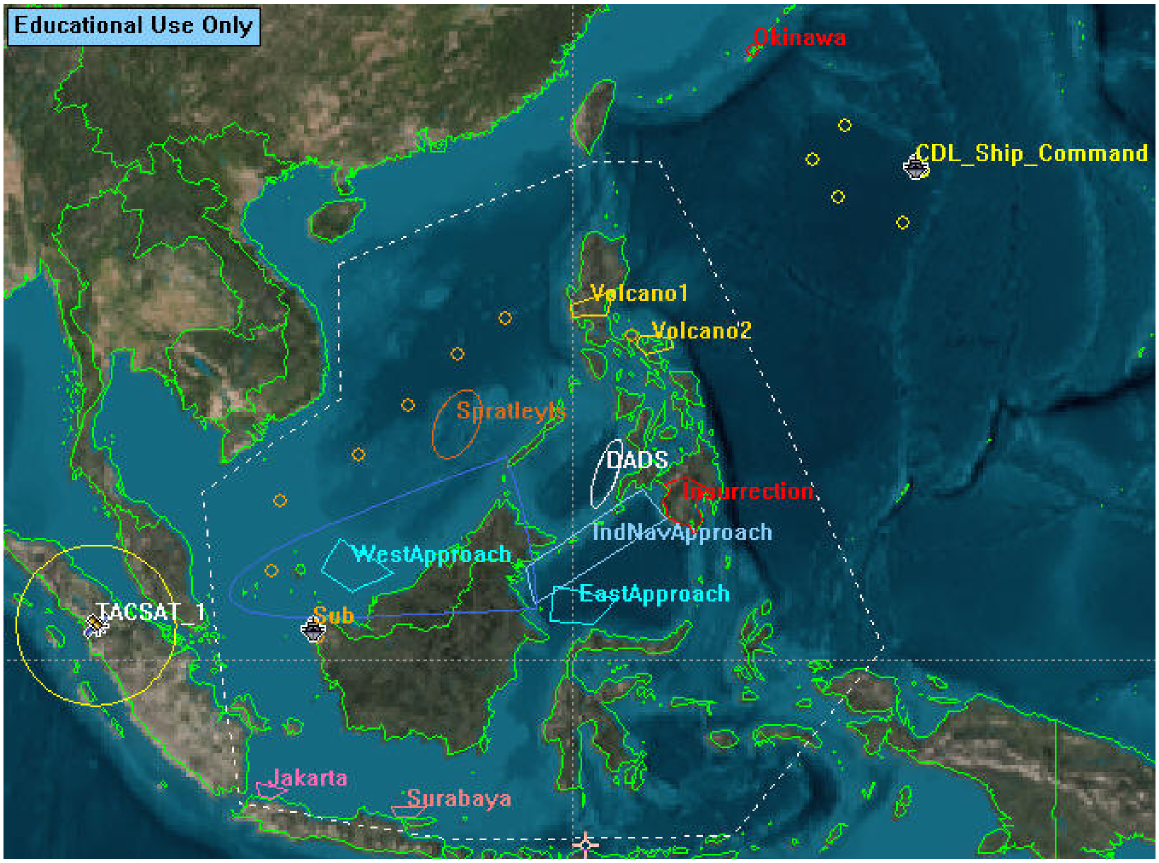

Figure 1- Area of Responsibility

b) Force structure. STK has the ability to input Navy assets or "objects" into a particular scenario. The figure below lists the facilities, ship assets containing CDL, and Army MIST station. The force structure for this scenario consists of the following:

1. Satellites. After the AOI was determined, two LEO satellite objects were inserted. To do this, the altitude, inclination, and RAAN needed to be specified along with the proper perturbed.
2. Common Data Link (CDL). The satellites need a ground system with which to communicate. Through the process of elimination and research CDL was chosen for the satellite downlink. To distribute CDL coverage thoroughly three ships were modeled with routes east of the Philippines.
3. Modular Interoperable Surface Terminal (MIST): Based on research with earlier TacSat experiments and ACTDs, MIST is in this scenario as a CDL compatible Army system. This object is represented by a road vehicle and is placed in the Philippines between the two volcanoes.
4. Potential launch and ground stations. Perth, Wallops, White Sands, Okinawa, Santiago are potential ground and launch stations.
5. Control Stations. Although not in this scenario, control stations play an important role in keeping the satellite along its current path.

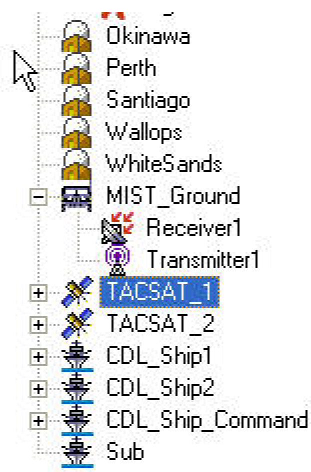

Figure 2- STK Objects in Object Browser

c) Payload parameters. Each TacSat is designed to contain an imagery payload, a SIGINT, and communications (transmit/receive antenna) to deliver the data. The capabilities utilized in STK assume that the SIGNIT and imagery are the same. Attached to each sensor are transmit/receive antennas that represent the communications link. The table of contents below shows what the STK object browser contains. Fixed and targeted (gimbaled) were analyzed using STK.

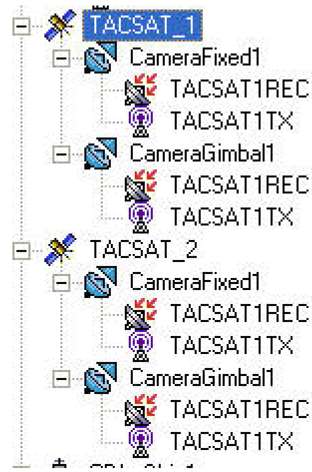

Figure 3- Attached Satellite Objects in STK Object Browser

d) Force Structure communication. The objects in the scenario need to communicate with the right systems and be able to relay data to compatible mission critical systems in the field.

1. Pointing/Targeting. This is how the sensor is steered to the target which can be any type of asset. Looking at the AOR in Figure 1, each TacSat will first pass over the Western Approach, then the Spratly area, then the volcanoes, transmit down to the MIST station as much information as possible and if it is not done transmitting, downlink to the CDL on the other ships in the Force Structure. Both targeted and fixed imagery are in the model. Targeting creates better access to the AOR, but does not come without its cost.

2. Chains. The TacSat constellation will communicate with CDL/MIST stations which may potentially relay to the ground stations (mobile units in the field). MIST and CDL must also be compatible and "chained."

e) Input researched payload parameters. After the chains were specified, the properties for each of the payloads needed to be looked at closer.

Sensors object properties. This includes ground coverage is a combination of factors which determine access/coverage are. These factors are slew/cone angle which help determine swath width.

1. *Communications object properties.* Each sensor has a respective transmitter and receiver associated with it. Since the sensor itself was gimbaled or fixed the communications antennas will move along with that particular sensor to pass data back and forth. So for gimbaled each antenna type on the TacSat constellation and the MIST/CDL ground stations were specified. STK allows flexibility by providing options for transmitters and receivers in the form of Simple, Medium, Complex transmit receivers. Simple just specifies the

frequency and the temperature. Medium specifies more detailed parameters and Complex specifies most antenna properties by inserting the beamwidth, gain, frequency, polarization, temperature (STK calculated or manually set), and modulation.

Table 1- STK Communications Properties

	STK Type	Dimensions (m)	Antenna Type	Frequency (GHz)	Gain (dB)	Power (dbW)	Data Rate (Mbps)	Polarization	Modulation	System Temp
TacSat Transmit (downlink)	Medium Source Transmitter	Unknown	Unknown	7.5	21	10	274	RHCP	BPSK	STK Calculate
TacSat Receive (uplink)	Medium Receiver	Unknown	Unknown	8.15	5	0	0.2	RHCP	OQPSK	STK Calculate
MIST/CDL Transmit (uplink)	Complex Receiver	1.9	Parabolic	8.15	45	17	274	RHCP	OQPSK	STK Calculate
MIST/CDL Receive (downlink)	Complex Source Transmitter	1.9	Parabolic	7.5	5	0	0.2	RHCP	BPSK	STK Calculate

f) Run simulation. Once all properties are verified, the scenario was simulated for a potential constellation of up to four satellites.

g) Change parameters and repeat. STK allows the user to insert an object, but it does not allow the user to shut an object off, so several iterations of this same experiment were ran for constellations for up to 4 satellites. Results in the appended reports will only include two through four satellites, their limitations/ increased coverage reports.

h) Report results. STK offers the user the ability to report on many aspects of the scenario. Satellite lifetime, for instance, reports a text file that shows the orbit on per day, weekly, monthly basis until it enters the earth's atmosphere. It also shows a lifetime graph of that data. Other reports generated include Access times from the sensors to the ground station and coverage reports for the uplink and downlink capabilities. Lifetime, access, and coverage reports will all be in the appended results.

Modeling, Simulations, Data

<u>Coverage</u>

In addition to the several iterations of altitude, GEO, LEO, HEO trade studies, coverage plot reports were generated for the specific areas inside the AOR designated. With a camera targeted on the center of the AOR, for one day coverage time (24 hours) is:

Table 2- Pointing towards the Center of AOR, STK Stats by Region Report.

Region Name	Num Accesses	Minimum (min)	Maximum (min)	Average (min)
Surabaya	0	0	0	0
Jakarta	0	0	0	0
EastApproach	4	0.76	2.984	1.862
IndNavApproach	9	2.138	10.141	5.519
WestApproach	8	2.036	9.946	4.717
Insurrection	7	0.337	3.399	1.998
DADS	15	8.366	15.285	12.021
SpratleyIs	11	73.775	98.381	91.615
Volcano2	11	11.888	14.903	13.128
Volcano1	11	11.872	13.289	12.526

If the imagery cameras are pointed towards the Volcano area, the coverage time for one day (24 hours) looks like this:

Table 3- Pointing towards Volcano 1, STK Stats by Region Report.

Region Name	Num Accesses	Minimum (min)	Maximum (min)	Average (min)
Surabaya	0	0	0	0
Jakarta	0	0	0	0
EastApproach	0	0	0	0
IndNavApproach	2	0	2.89	0.511
WestApproach	0	0	0	0
Insurrection	2	0.505	2.407	1.273
DADS	2	2.105	6.129	4.206
SpratleyIs	4	3.587	6.529	4.959
Volcano2	16	29.83	52.962	41.02
Volcano1	9	75.576	81.371	80.089

Downlink Access

Access to the ground stations for downlink is another important issue. For a downlink MIST station located near the volcanoes and imagery pointing at two different areas, the following table shows access times and quantity for a 17-day period.

Table 4.

Pointing Area	Minimum Access (min)	Maximum Access (min)	Number of Accesses in 17 days
Volcano	1.82	9.77	246
AOR center	0.04	1.00	19

Conclusion

Imagery coverage areas for different pointings are shown above. If the satellite points to the north, the areas to the south will not be covered. The opposite is also true, if the satellite points to the south, the north will not be covered as well.

From the access table for downlink access, a MIST station in the field located near the volcanoes would not have very good access to the imagery data and would only experience downlinks intermittently. This analysis is for only one TacSat and not two. Two satellites would double the access. Detailed reports on access and pointing will be in the thesis final package.

Placement of the ground station becomes very important with respect to pointing of the imagery camera. The satellite will need to have enough onboard processing and mechanical ability to quickly maneuver imaging cameras and downlink to the ground stations. Both coverage and downlink capability must be examined further to determine downlink placement. Coverage areas can be altered as well to optimize pointing.

Coverage of the full AOR is determined by the sensors' pointing. If the imagery cameras point to the center of the AOR, the downlink MIST station could be located at some other point. This means the satellite will need to maneuver the payload to complete the mission and downlink or have an alternate downlink. This analysis only incorporates downlink and imagery sensors pointed in the same direction. Alternate downlink designs were not analyzed. The results show that the best way to downlink to an area that will allow the most access to downlink is to point the camera at it first. These results do not include environmental constraints of the Philippines Sea Scenario. Those constraints will further impact the coverage and access calculations.

APPENDIX B. TACSAT SENARIO

Coalition FORCEnet Study – Operation Philippine Comfort Scenario

1. TTCP's MAR group has set up Action Group 6 (AG-6) to study the coalition impact of participating in the USN FORCEnet programme. The intention is to provide guidance to each Nation (AUSCANNZUK) in terms of identifying opportunities to participate in FORCEnet, and the operational benefits that might result. The aim is to assist each Nations decision making process, by supporting their criteria for evidence to approve such an investment.

2. AG-6 have outlined a programme of work to identify technical opportunities, and both high and low level operational analysis, that will leverage individual Nations capabilities, previous MAR AG-1 collaborative work, and also utilize MSc studies by the U.S. Naval Postgraduate School (NPS) systems engineering students. Discussion has identified the requirement for a feasible Coalition scenario, to act as the framework for the various modeling efforts and that the *Operation Philippine Comfort – CJTF* scenario, already used for U.S. demonstrations of FORCEnet components, might be appropriate. The scenario can be set in any timeframe through to 2015, though early examples were set in Nov 2003.

Scenario Description

3. Historical Setting: Oil has been confirmed in the Spratly Islands Region in 2008. This has led to greater territorial dispute and re-interpretation of the Economic Exclusion Zone by the five nations laying claim to the Spratly's and their potential mineral wealth. International arbitration has resulted in the Philippines being awarded major holding in the disputed area in 2010; Indonesia has routinely stated that the U.S. public support of the Philippines' claims was capricious, and in retribution has done little to quell the indigenous anti-U.S. fomentation by its Islamic fundamentalists. While Indonesia is not likely to embark on overt unilateral military action against the Philippines, they are likely to attempt to capitalize on opportunistic regional instability.

4. The scenario opens with an internationally compelling natural humanitarian disaster - public sentiment requires relief action an the part of each nation. Each nation has in the vicinity assets with some dual use capability (naval/humanitarian relief) so their initial response can be measured in days not weeks. The trade space for modeling the force is that some portion of the U.S. ESG will not be available. The injection of the Indonesian Naval threat will be evolutionary and will begin after the Nations have already very publicly committed to the humanitarian mission, thus removing the opportunity to just not participate.

    1. From the Indonesian perspective opportunity knocks in 2015: the Philippines are affected by two large volcanic eruptions affecting the centre of the country (Luzon), and the overall disruption leads to a political crisis and change of

government. Other nations provide support with humanitarian and disaster relief, but whilst this effort gathers pace, Muslim factions in the southern province of Mindanao use the opportunity to forment trouble and achieve their own goal of a separate secular state. The coalition support then widens to include peace making/peace enforcement, and the U.S. dispatch an Expeditionary Strike Group (ESG) with an amphibious component to ensure that disaster relief is not impeded, and to provide additional land support to Philippine ground forces facing the insurgents. In turn this triggers increased Indonesian support (previously covert) to the separatists, and their naval units (SAG and SSK) attempt to oppose access by the ESG.

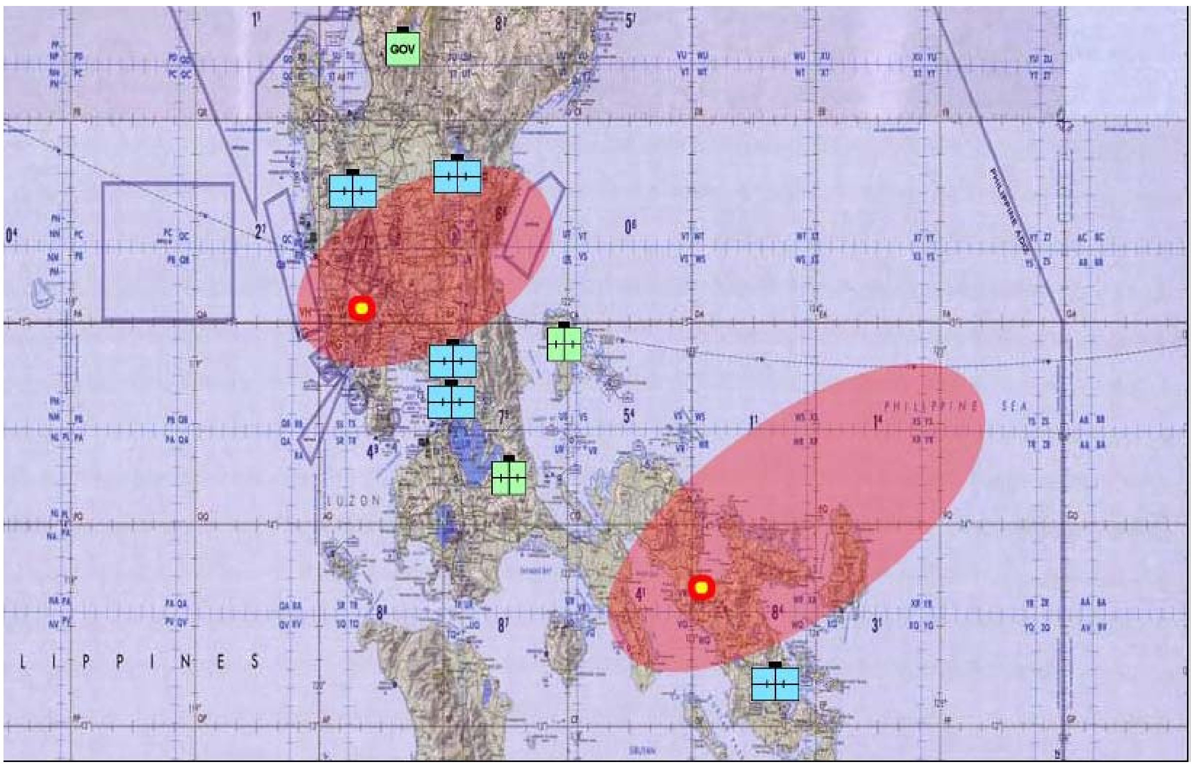

Figure 1 – Natural Disaster Triggers Scenario

Chronology. The following is the outline timeline:

Table 1 - Timeline

Day	Event:
D0	Volcanic eruptions, Philippines asks for international assistance with disaster and humanitarian relief
	Tensions over crisis response cause fall of Philippine Government
D+1	Insurrection starts. CNN reports rebel forces have taken government hostages and are threatening NGO entry/aid efforts.
D+1	Commitment of ESG
D+4	Indonesian declaration of support to insurgents. SAG and SSK deployments
	Stabilisation forces delivered ashore

FORCEnet Capability Assumptions

2. The nature of the ESG lends itself to accommodating coalition enhancements to give a scalable and compassable force. The intent of the study is to quantify the degree to which FORCEnet improves its changes of success. Table 2 lists the broad benefits that would expect to be enjoyed by an ESG/CSG with a coalition element at various levels of FORCEnet capability. Benefits accumulate with increasing FORCEnet level.

Table 2 – FORCEnet Benefits/Characteristics

FORCEnet Level	Benefits/Characteristics:
0	No FORCEnet**.** Vessels use voice radio and Link 11 or 16 to share situational awareness and C2 data. Platform-centric in character.
1	Filtered, delayed, low bandwidth (dialup) FORCEnet (like ‘no FORCEnet’, but higher fidelity/faster updates). ESG/CSG has access to reach back and has the ability to distribute intelligence information gained from that to all ESG/CSG members. Information from organic sensor and intelligence data is available with some time delay throughout ESG/CSG. Recognized maritime picture (RMP) which fuses organic and other ESG/CSG data is distributed with minor time delays.
2	Real-time targeting information gained from any U.S. or coalition asset/source (when latter is technically capable) is available to all ESG/CSG vessels as required. Access to targeting information is assured within understood limitations. Information accuracy, timeliness and coverage continuity are assured up to predefined levels. Rapidly updated RMP is available to all ESG/CSG vessels.
3	Weapons systems are networked but are only able to be controlled by national authority.
4	Vessels of all coalition nations are technically and politically/militarily able to offer weapons systems as a network service for command by approved authorities from any of the nations within the ESG/CSG.

Specific ESC/CSG +/- coalition capability options to explore in the modeling are shown in Table 3. These options are mapped to the benefits listed in Table 2

Table 3 – FORCEnet Options

Option	Description	Map to Benefits in Table 2
I (do nothing)	Small size (all U.S.) ESG force, fully FORCEnet capable	U.S. part (level 3) No Coalition
II (do minimum)	Added Coalition ships, but not FORCEnet capable (i.e., larger overall force)	U.S. part (level 3) Coalition part (level 0)
III	Intermediate FORCEnet capability to the additional Coalition ships	U.S. part (level 3) Coalition part (levels 1 or 2)
IV	Full FORCEnet capability to entire force	U.S. and Coalition Units (level 4)

Maritime Storyboard

7. Volcanic eruptions on Luzon have caused widespread civilian distress, and Naval and Marine forces from the Essex ESG (originally transiting South East Asia en-route to the Arabian Gulf) are diverted. The U.S. commit the force to Humanitarian Aid and Disaster Relief (HA-DR) tasking, involving airlift, medical and material requirements. The ESG is 72 hours from Republic of Philippines (RP), when it is ordered to divert to provide humanitarian assistance/relief and to be prepared to assume the role of Maritime Component Commander (MCC). Other nations also promise relief assets, to be identified over the next 48 hours.

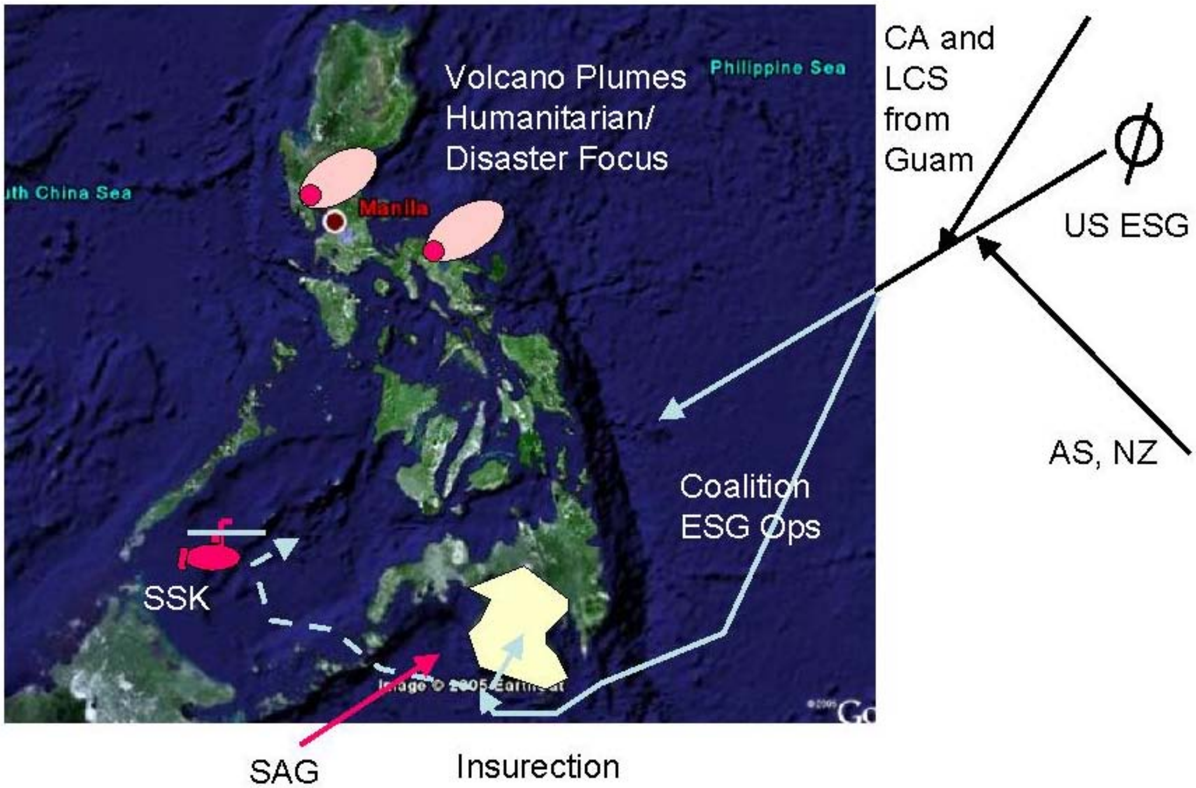

Figure 2 – Maritime Storyboard – Assembly of ESG

8. Fundamentalist rebels (ASG) remain active on southern Philippine islands, and increased force protection measures are applied to all units transiting within the vicinity. The ESG is briefed to anticipate the possibility of providing assistance to U.S. and RP ground forces, and at T+36, the MCC re-roles assets to provide for enhanced Force Protection of MCC forces and NGOs.

9. At T+48 (1500Z07NovXX) Indonesia announces support for ASG. The statement:

- praises the gallant fight of the Muslim freedom fighters and their valiant struggle to achieve independence on for the Muslim Republic of Mindanao.
- criticizes the Philippine Government not recognizing this new republic.
- criticizes the U.S. Government for its support of the Philippine Government and its suppression of liberty.

To show its support of Mindanao, Indonesia announces that it will send a naval force northward up the Sulu Archipelago on a Freedom of Navigation (FON) transit to Mindanao.

They do not announce what that force will do once it arrives in the area, but it is likely to be based on their recent major sea exercise off the south-eastern point of Borneo. This featured:

- 2 cruisers, 5 frigates and 1 amphibious ship have been operating as a single force, conducting anti-submarine operations against the 2 Kilo submarines for about five days
- The exercise was observed by a nearby Australian frigate that also monitored the communications traffic

- The Kilo's appear to be fairly proficient. National sensor support confirms that the submarines have not returned to port near Jakarta, there is no SIGINT information to confirm their whereabouts, and the Kilo positions have been unknown for about 50 hours

10. The ASW vignette then runs for 6 days, and covers the approach of the ESG to the operating area near Mindanao, the monitoring and shadowing of Indonesian naval units in the Sulu sea as the scenario unfolds, forming the first, and then a second SAG. The ESG then has to localise two Kilo class SSK using a mixture of assets: MPA, SSN, LFAS and deployable barrier sensors laid by Littoral Combat Ships (LCS), which is supported by an operational deception (Opdec) plan covering the major surface units of the ESG. Timeline considerations include:
    - Virginia-class SSN based at Apra Harbor (Guam) could be off Mindanao in about 41 hours, plus whatever time is required to make ready for sea.
    - Maritime Patrol Aircraft (MPA) operate out of NAS Agana. There could be one aircraft continually on-station for up to two-weeks.
    - A five-ship squadron of Littoral Combat Ships (LCS) in Apra Harbor, with sufficient undersea surveillance modules to equip two of these ships with deployable surveillance. With a 40-kt SOA, LCS can be on-station off Mindanao in about 26 hours, plus whatever time is required to make ready for sea
    - A TAGOS ship (Cory Chquest) equipped with Low-Frequency-Active Sonar (LFAS) can be off Mindanao in about 60 hours, plus whatever time is required to make ready for sea

11. Scenario Order of Battle

ESG ORBAT prior to Coalition enhancement:

Essex LHD2	Winston Churchill DDG81
Curtis Wilbur DDG54	City of Corpus Christi SSN705
Juneau LPD10	Niagara Falls LCS1
Ft McHenry LSD43	Cumberland Falls LCS2
Antietam CG54	Bushkill Falls LCS3

Coalition ORBAT

Canada

A. High-intensity operations (combat expected)

On warning + 10 days, a high readiness Cont TG and sustain the TG for 60 days, including transit time.

MARPAC (Esquimalt) would provide

- 1x FFH,
- 1x DDG or AOR, and organic air.

MARLANT (Halifax) would provide

- 1xFFH,
- either the DDG or AOR that MARPAC did not provide, and organic air.

Also:

- 1 x SSK could also deploy with the TG from either the East or West Coast.

B. Medium-intensity operations (significant threat to deployed forces expected),

Same configuration as in(A). but for a period of 12 months (over 2 ROTOs), including transit time.

C. International contingency operations

1 x FFH from MARPAC sustained for 60 days or 12 months (over 2 ROTOS), including transit time.

New Zealand

Suitable subsets chosen from:

- 2 x ANZAC Class FFG (HMNZS Te Mana and Te Kaha)
  - Speed: 27+ kts, Range 6,000 nmi @ 18 kts
  - Weaponry: 5” gun, CIWS, Seasparrow Mk 41 air defence missile system, 2 x MK 32 Mod 5 Surface Vessel Torpedo Tubes , 50 cal guns
  - Comms: Link-11, 64 kbs INMARSAT, VHF/UHF voice, HF Signals System, HF/UHF subnet relay
  - GCCS-M
  - CENTRIXS (single COI at a time)
  - Carries 1 KAMAN Super Seasprite helo
- 1 x Multi role vessel (due 2006)
  - Capable of embussing up to 250 troops, and a range of equipment including: 2*NH90 or SeaSprite helos and LAVs
  - Able to land troops and supplies without established port.
- 1 x Replenishment at sea vessel (HMNZS Endeavour)
  - Speed: 14 kts, Range 10,000 nmi
- 1 x Hydrographic research vessel (HMNZS Resolution)
  - Speed: 11 kts, Range 21,500 nmi.
- 1 x Diving support vessel (HMNZS Manawanui)
  - Speed: 11 kts, Range 5,000nmi
- 6 x RNZAF P3-K Orion
  - Currently undergoing an upgrade of communications, navigation and sensing capabilities
  - Wide range of sensing systems
  - Comms: Link-11, HF/UHF Voice
- 5 x KAMAN SH-2G Super Seasprite
  - Capable of carrying torpedoes, depth charges and maverick missiles. M60 machine guns
  - Comms: Voice/Link-11

United Kingdom

TBP

Australia

2 x ANZAC FFH
2 x FFG
1 x Air Warfare Destroyer (AWD)

Indonesian Naval ORBAT:

Type	Status	Armament	Qty	Location
Kilo SS	Operational	8 Strela-3 (SA-N-8 Gremlin) 18 VA-111 Torpedoes	2	At Sea
Parchim Corvette	Operational	2 quadruple SA-N-5 (24 missiles) 2 twin 16-in torp tubes (400-mm) 4 KH-35	8	6 At Sea 2 in Surabuya
Fatahilah Corvette	Operational	2 twin 16-in torp tubes (400-mm)	6	2 At Sea 4 in Surabuya
Van Spijk Frigate	Operational	1 76mm gun 8 SS-N-14 ASCM	3	2 At Sea 1 in Surabuya
Kihajar Dewantara Frigate	Non-operational	1 76 mm gun	4	In Surabuya
Patrol Boat PSK-M	Operational	4 KH-35	12	At sea
Tacoma LST	Operational	2 .50cal	3	1 At Sea 2 In Surabuya

Concept of Analysis for AG-6 Modeling

12. The Concept of Analysis (CoA) for AG-6 modeling includes both high and low level operational Analysis (OA). The high level work is essentially at the campaign outcome level, whilst the lower level work is at the vignette or encounter level. The overall hypothesis is:

H1. FORCEnet gives the ability to compose a well trained, coalition agile mission group, which will achieve military aims quicker, with less resources, and at lower risk.

The planning workshop also identified the following top-level Measures of Effectiveness (MoE), and lower level benefits or ‘qualities’ of the FORCEnet enabled taskgroup:

Top level MOEs:	Qualities:
Campaign Success (Effectiveness)	Agile/Flexible/Adaptive
Economy of Effort (Efficiency)	Plan/Train/Rehearse/Execute/Regenerate
Time to Capability (Timeliness)	Collaborative Working
Minimise Attrition (Risk)	Quality of Information
	Shared Awareness
	Self Synchronising
	Distributed Combat Elements

Table 4 – MoE and Qualities

13. **Integration of vignettes into High Level Campaign analysis.** There are two discrete levels of OA work: high-level campaign modeling (using NSS, DARNOS or MANA), and lower-level vignette or encounter modeling, exploiting national work, the previous MAR AG-1 study, and the team projects of system engineering MSc students from NPS. It is the intention that all use a common representation of the scenario, and of the options outlined in para 4 above, and that the more detailed lower level work is used to ‘underpin’ or calibrate the relevant aspects of the high level models.

14. The output of the lower-level modeling can be characterised either as a Measure of Performance (MoP), or as the MoE for that element in isolation (which are then capable of being used as building blocks for the higher level analysis work). In the event that there are problems with the high level models, the following picture shows how the ‘slices’ of lower level work may be aggregated upwards to produce the same outcome. The eight slices cover the sequential phases of the operation, followed by recovery & regeneration:

- Training & Planning as the Coalition ESG force ‘gels’ together during the transit and assembly phase (NPS work plus DARNOS).
- A littoral transit phase against a FIAC threat (MAR AG-1 work with MANA).
- ASW against the Kilo threat (MAR AG-1 work with Queue Theory)
- ASuW against the SAG threat
- AAW and/or ASMD should the Indonesian forces achieve launch position against ESG (NPS work using Extend model)
- Amphibious offload, to put the forces ashore to back up the RP troops against the insurgents
- Naval Fires support, if appropriate to land campaign (DARNOS, and potentially, NPS)
- MIO, to stop Indonesia reinforcing the insurgent ashore, by sea (MAR AG-1 work with Queue Theory).

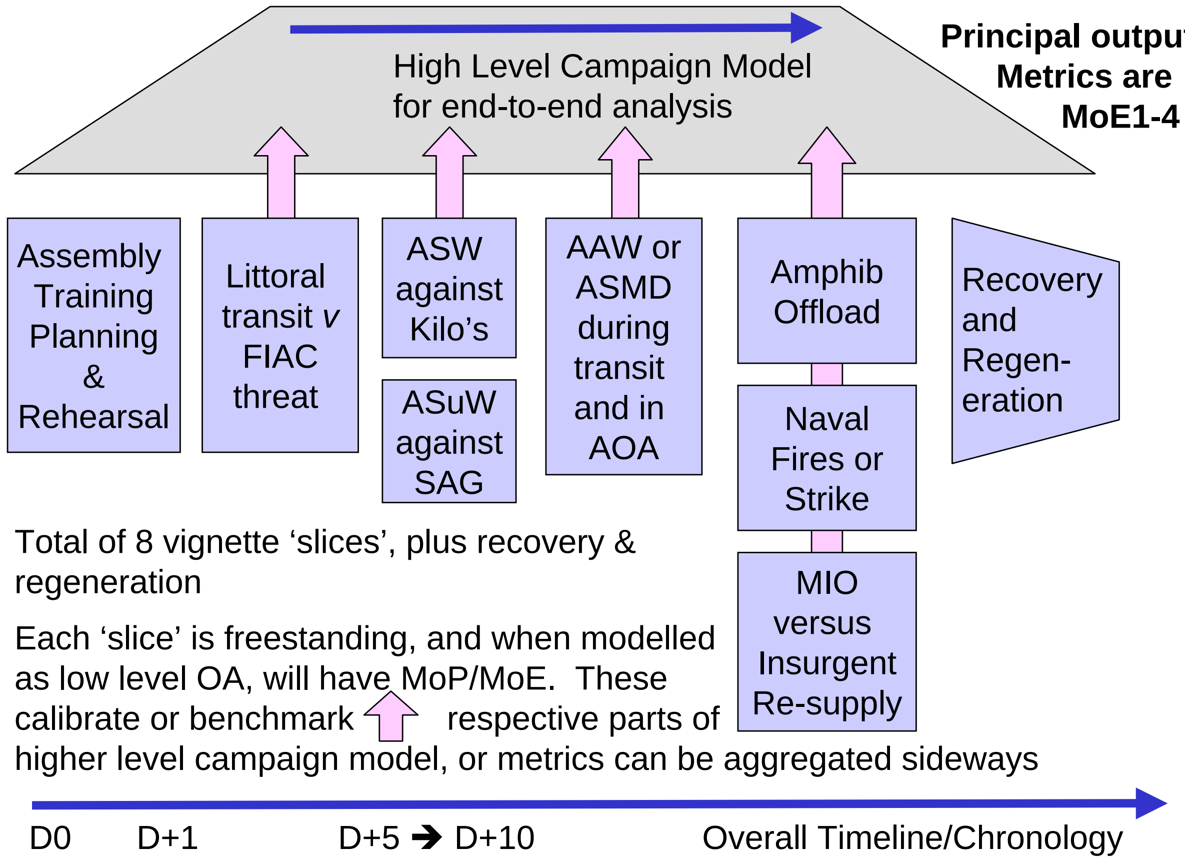

Figure 3 – Overall Study Structure

15. The only issue with this simplified picture, is that it presents an almost 'linear', attrition based view of the operation, whereas Network Centric Warfare is intended to capture the parallel application of effort to many aspects simultaneously, and by using adaptive behaviour, to achieve Effects Based Operations. These aspects may be captured by the high-level campaign model, and the use of 'sideways' aggregation of the lower level slices represents a fallback, in the event that the campaign work is not completely successful. The high level metrics (MoE1-4), and the contribution made by the lower level measures are shown below:

High Level MoE:	Contributing Elements and Notes:
MoE1 Time to Capability	Number of MEU major Amphib units delivered time to achieve Gives credit for safe delivery ashore, and factors in transit speed, i.e. Fn will reduce timeline, by incorporating planning and rehearsal into transit
MoE2 Economy of Effort	Cost, for fuel and munitions used in Campaign
MoE3 Risk	Minimise blue attrition - sum total of unit losses for all eight slices (assemble, Littoral transit, ASW, ASuW, AAW/ASMD, Offload, NFS and MIO)
MoE4 Campaign Success	Probability of success for each warfighting slice (Littoral transit, ASW, ASuW, AAW/ASMD, NFS) multiplied by Time to Capability (MoE1) minus MoP for MIO phase Safe delivery of Campaign effectors (landing force ashore), minus red's ability to interfere with/ degrade our operations by reinforcing insurgents

Figure 4 – Model and Metric Integration

16. It is likely that this view will be refined as the study progresses, and in particular that the lower level slices can also be aligned with the 'FORCEnet Qualities', identified in Table 4 above.

TTCP MAR AG-6 FORCEnet Systems Engineering Study Philippines Scenario: Vignette Breakdown and Measures of Effectiveness

The TTCP MAR AG-6 scenario plan lays out a timeline of events, which is broadly as described in Figure 1 below. Here a U.S.-led Expeditionary Strike Group (ESG) or Carrier Strike Group (CSG) is joined by elements from Australia, New Zealand, Canada and the United Kingdom, who then assist in humanitarian relief and insurgency suppression in the Philippines.

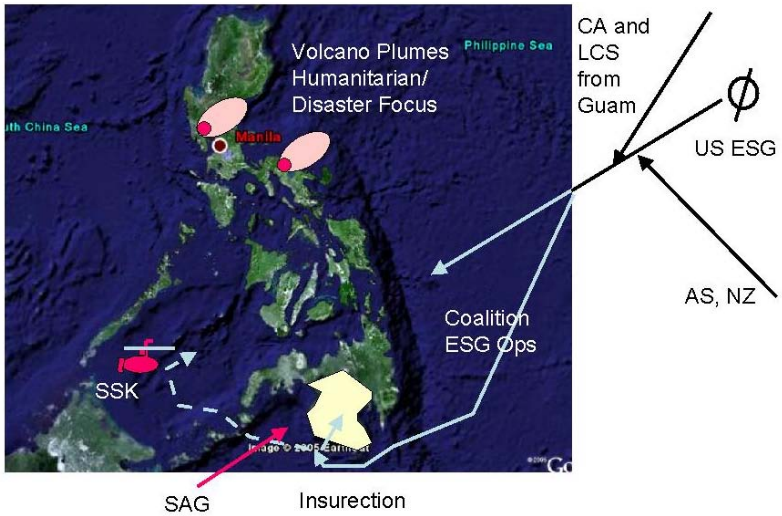

Figure 1 Graphical overview of scenario.

In order to break the scenario down into specific tactical situations a second map, shown in **Figure 2**, has been developed. Amphibious offload, maritime interdiction operations and naval gunfire support are not shown as they are all likely to occur close to the landing point (which has not yet been determined) and would be occurring at a similar time to one another.

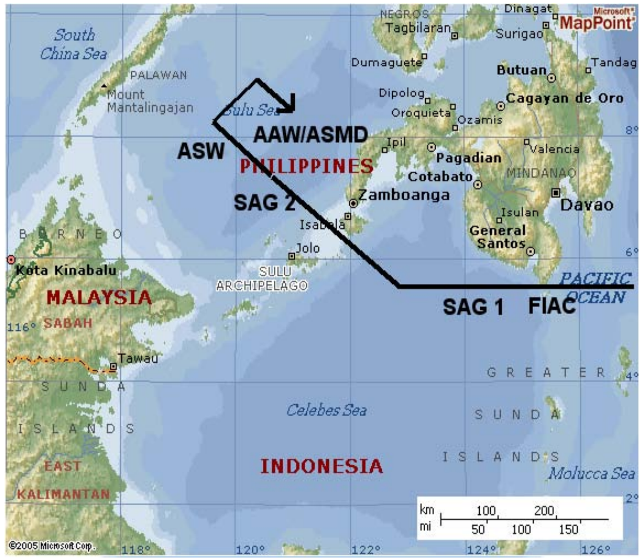

Figure 2. Tactical situation plan for TTCP MAR AG-6.

Orbats are provided here on the basis that often only a selection of the assets listed would be used in specific studies.

Phase 1 - Training & Planning as the Coalition ESG/CSG force 'gels' together during the transit and assembly phase

Description. FORCEnet enables connected platforms and organizations to plan and train together while assembling the force. The assembly phase is notionally shown in Figure 1.

MOP. Potential high-level MOP are presented here. Performance in each of vignettes explored here will contribute to these overall measures.

1.1 Disposition of COP prior to arrival in theatre as compared with that after arrival.
1.2 Timeline to geolocate, identify and act on targets of interest.
1.3 Level of understanding of commander's intent.

Potential Executor/Models. (NPS work plus DARNOS).

Phase 2 - A littoral transit phase against a FIAC threat

Description. ESG/CSG transiting Sarangani Strait is attacked by FIAC manned by insurgents. FFG/LCS defend the high value units (HVU: LSD (1), LPD (1), LHD/CVN (1), NGO Vessels) from the attackers. Figure 3 shows the course taken by the ESG/CSG. The littoral environment offers the opportunity for FIAC to attack from close to

Mindanao where they can be initially concealed in coastal traffic; or for them to attack from close to Sarangani or Balut Islands where they could use the islands for concealment.

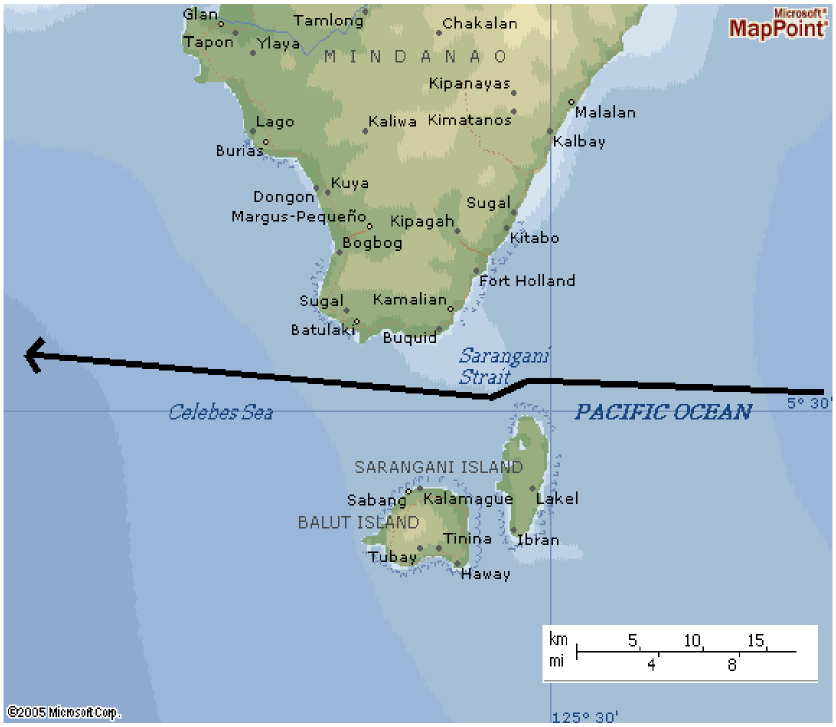

Figure 3. Course of ESG/CSG through Sarangani Strait, where a FIAC attack is experienced.

Orbats.
Blue Force. Combat: LCS (3), 2 DDG, 2 Coalition FFG/DDG (2), MPA/AWACS/ UAV/helos. HVU: LHD/CVN(1), LPD(1), NGO vessels

Red Force. 5 - 20 type 1 (armed with RPG/large blast bomb - range 500m) or 2 - 5 type 2 FIAC (armed with multiple launch rockets – range 8 km)

Force Objectives
Blue. Defend HVU and continue on course.
Red. To destroy the HVU. Suicidal psychology.

Relevant FORCEnet levels. Levels 0 – 4.

MOP. Potential high-level MOP are presented here. Performance in each of vignettes explored here will contribute to these overall measures.

2.1 Average detect to kill time.
2.2 Probability/Number of leakers.
2.3 Probability of achieving raid annihilation
2.4 Number of HVU soft-killed

2.5 Number of Blue combatant craft soft-killed
2.6 Time for contacts to propagate to all vessels in fleet. (Time to propagate COP)

Potential Executor/Models. Extension of TTCP MAR AG-1 work with MANA.

Phase 3 - ASuW against the SAG threat

Description: Red force forms surface action group (SAG) during approach to Sulu Archipelago. Blue force monitors and shadows SAG as it passes through the archipelago. Red force forms a second SAG once it arrives in the Sulu Sea and Blue force continues its monitoring/shadowing role. See Figure 2 for a map plan.

Blue Force ORBAT
Combat: 3 LCS, 1 SSN, 2 DDG, 2 Coalition FFG/DDG, MPA/AWACS/UAV/helos
HVU: LHD/CVN(1), LPD(1), NGO vessels

Red Force ORBAT
2 Parchim Covette, 3 Van Spijk FFG

Blue force objectives
Monitor and shadow Red force SAG

Relevant FORCEnet levels. Levels 0 – 2.

MOP. Potential high-level MOP are presented here. Performance in each of vignettes explored here will contribute to these overall measures.

3.1 Amount of time SAG within sensing range.
3.2 Efficiency of asset allocation for monitoring duty.
3.3 Ability to maintain RMP (accuracy, timeliness etc.).

Potential Executor/Models. Unassigned

Phase 4 - ASW against the Kilo threat

Vignette Description. As shown in
Figure 2, once the ESG/CSG has passed through the Sulu Archipelago into the Sulu Sea it must localise two red force submarines. It will use a range of assets and sensors to do this.
Figure 4 shows the concept of benefit that TTCP MAR AG-1 saw from network enabling the fleet in such a tactical situation

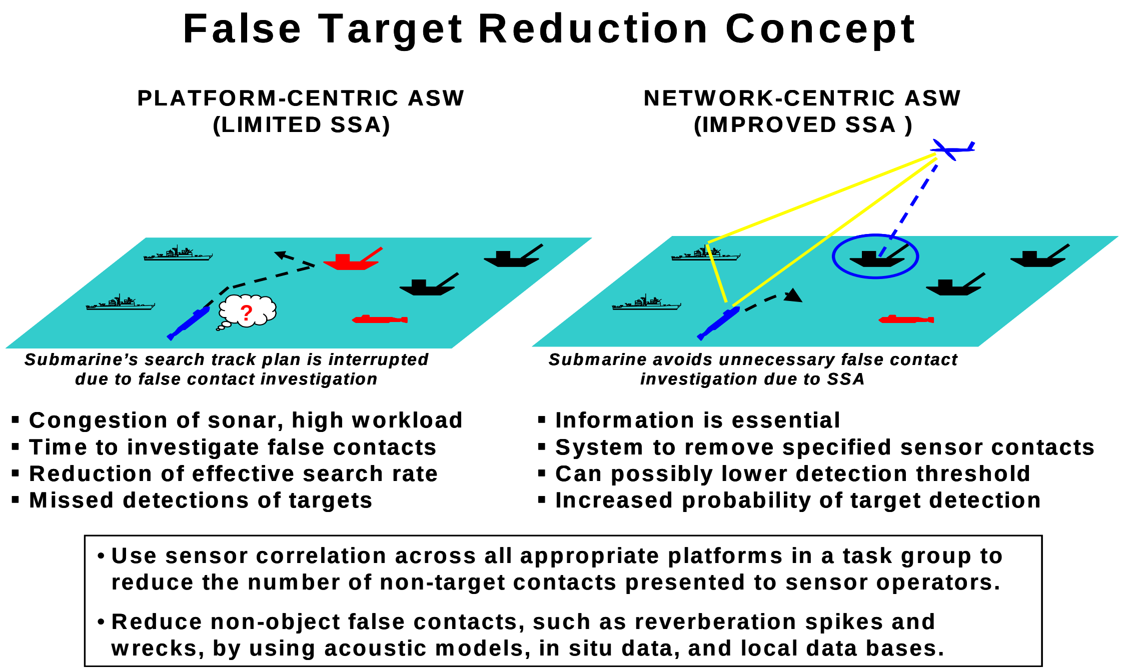

Figure 4. TTCP MAR AG-1 ASW NCW Concept.

ORBATs
Blue - A mixture of assets: MPA (1 continuous equivalent U.S. or coalition), SSN (1), LFAS and deployable barrier sensors laid by LCS, (3).
Red - 2 Kilo submarines.

Force Objectives
Blue - ESG/CSG aims to localize the red force submarines.
Red - Unknown.

Relevant FORCEnet levels. Levels 0 – 2.

MOP. Potential high-level MOP are presented here. Performance in each of vignettes explored here will contribute to these overall measures.

4.1 Probability of locating and classifying enemy submarines
4.2 Time taken to locate and classify enemy submarines

Potential Executor/Models. Extension of TTCP MAR AG-1 work with Queue Theory.

Phase 5 - AAW and/or ASMD should the Indonesian forces achieve launch position against ESG/CSG

Vignette Description. During or after the hunt for the SSK Red force may launch an air or missile attack.
***Figure* shows this occurring somewhere in the Sulu Sea.**

ORBATS
Blue force - Combat: LCS (3), DDG (2), U.S. E-2C (1), Coalition FFG/DDG (2).
HVU: LHD/CVN(1), LPD(1)

Red force - 2 Parchim Covette, 3 Van Spijk FFG, 2 Kilo submarines.
Or:
SU-27 (8)

Force Objectives
Blue - To defend ESG/CSG against air/missile attack.
Red - To attack ESG/CSG from the air/with missiles.

Relevant FORCEnet levels. Levels 0 – 4.

MOP. Potential high-level MOP are presented here. Performance in each of vignettes explored here will contribute to these overall measures.

5.1 Average detect to kill time.
5.2 Size of supportable engagement envelope.
5.3 Probability/Number of leakers.
5.4 Probability of achieving raid annihilation
5.5 Number of HVU soft-killed
5.6 Number of Blue combatant craft soft-killed
5.7 Time for contacts to propagate to all vessels in fleet. (Time to propagate COP)

Potential Executor/Models. NPS work using Extend model. MANA is a possibility as an alternative.

Phase 6 - Amphibious offload, to put the forces ashore to back up the RP troops against the insurgents

Vignette Description. Once seaborne threats have been removed or subdued preparation is made for amphibious offload of troops and equipment to assist RP troops against the insurgents. ISR requirements must be met for a beachhead landing including littoral reconnaissance prior to landing and ongoing surveillance during landing. Liaison with forward RP elements throughout is necessary.

ORBATs
Blue - Combat: LCS (3), Coalition FFG/DDG(2), DDG (2), MPA/UAV/helos
Amphibious offload: LPD (1), LHD/CVN(1), NGO Vessels, Coalition amphibious offload ships (e.g. UK LSD(A) or NZ MRV).
Red - Land insurgent elements.

Force Objectives
Blue - Support safe landing of troops and equipment.
Red - Disrupt Blue force landing at all costs.

Relevant FORCEnet levels. Levels 0 – 2.

MOP. Potential high-level MOP are presented here. Performance in each of vignettes explored here will contribute to these overall measures.

6.1 Time to complete amphibious offload.
6.2 Ability to co-ordinate ISR assets before and during offload to monitor sea and land threats.

Potential Executor/Models. MANA is a possibility here.

Phase 7 - Naval Fires support

Vignette Description. During HA phase of amphibious offload, truck-loaded rocket launchers attack coalition amphibious forces. Trucks are either well-camouflaged or disguised as ambulances mixing with other HA assets. Trucks commence firing unguided rockets at landing marines and landing craft. The trucks are located on cliff-tops or other inaccessible locations which prevent direct marine counter-attack, therefore marines request fire support from coalition ships.

SACC determines fastest available asset is NSFS, therefore AWD and 1xANZAC are ordered to conduct NSFS ops to suppress trucks.

MOPs. Potential high-level MOP are presented here. Performance in each of vignettes explored here will contribute to these overall measures.

7.1 Time and number of rounds taken to suppress truck attack.
7.2 Number of trucks destroyed vs. number of trucks escaped.
7.3 Accuracy of first round falls of shot.
7.4 Time taken from call to fire, to first round impact.
7.5 Time taken from first anti-coalition attack to first round impact.
7.6 Time taken from first anti-coalition attack to BDA confirming target neutralized.

ORBATs
Blue - 1 x ANZAC

1 x AWD
1 x UAV (RAN owned or U.S. owned)
Marine spotter(s)
Red - 4xtrucks with rocket launchers hidden or disguised, possibly mobile.
Neutral - Refugee camp 500 yards form trucks

Relevant FORCEnet levels:

FORCEnet level 0. Marines spotters provide target info (MGRS coordinates) by voice over radio only to NFSF ships.

FORCEnet level 1

- Targeting from marines only (no UAV) via GPS/laser spotting device
- Delayed UAV info

FORCEnet level 2

Targeting high-resolution video feed from UAV/marine spotters freely available.

Example Storyboard

- During HA phase of amphibious offload, truck-loaded rocket launchers attack coalition amphibious forces.
- Trucks were either well-camouflaged or disguised as ambulances mixing with other HA assets.
- Trucks commence firing unguided rockets at landing marines and landing craft. Trucks located on cliff-tops or other inaccessible locations, prevent direct marine counter-attack, therefore marines request fire support from coalition ships.
- SACC (embarked on amphibious ship) determines fastest available asset is NSFS
- AWD and 1xANZAC are ordered to conduct NSFS ops to suppress trucks.
- SACC coordinates NSFS ships to spotter(s)
- Senior NSFS ship contacts spotter
    - No FORCEnet: trucks visible to spotters (but out of range)
    - Intermediate/Full FORCEnet: trucks not visible: UAV deployed (from owner) to verify targeting
    - (Assume this is a daylight operation)
- Spotter commences fire missions on truck (Assume a truck is visible)
- At some point, all visible trucks are destroyed or have left the area. Red fire ceases.
- Commence BDA ops:
    - Using air assets (UAV, helicopters, CAP a/c)
    - Option to prosecute escaping trucks using air assets or NFSN ships, or ARH helicopters from RAN amphibious ship

Potential Executor/Models. DARNOS, and possibly, NPS. MANA is a possibility as an alternative.

Phase 8 - MIO, to stop Indonesia reinforcing the insurgent ashore, by sea

Description. Indonesian forces have sent troops and supplies to assist the insurgents ashore. Method of entry is by unmarked civilian vessels. Blue force attempts to prevent this entry by forming a MIO barrier. All vessels passing through this barrier are queried and as many as possible are searched. Figure 5 shows a representation of the adaptive redeployment concept modelled by TTCP MAR AG-1 for MIO.

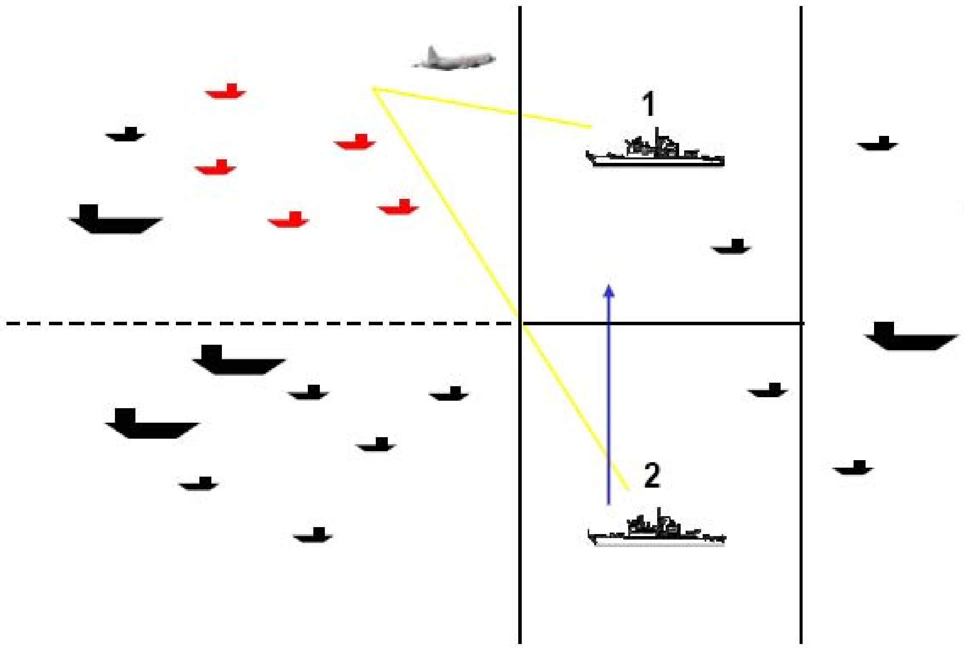

Figure 5. Concept of adaptive redeployment within maritime interdiction operations as modelled by TTCP MAR AG-6.

ORBATs

Blue - DDG (2), LCS (3), Coalition FFG/DDG (2). 2 RHIBs and boarding parties available per vessel. MPA/AWACS/UAV/helos.

Red - Insurgents potentially utilizing:

- Up to 50 fishing boats
- 10 small craft/coastal traders
- 4 large merchants

Neutral - Up to 50 fishing boats, 10 small craft/coastal traders, 4 large merchants (Legitimate craft, possibly transporting refugees from disaster areas

Force Objectives

Red - To evade the MIO barrier and to reach land.
Blue - To prevent reinforcements and supplies from reaching land.

Relevant FORCEnet levels. Levels 0 – 2.

MOP. Potential MOP are presented here. Performance in each of vignettes explored here will contribute to these overall measures.

8.1 Number of Critical Contacts of Interest (CCOI) successfully inspected vs. total number of craft in the AO
8.2 Percentage of correctly identified CCOI in the Recognized Maritime Picture (RMP)
8.3 Percentage of CCOI missed by the MIO
8.4 Number of incorrectly identified craft boarded
8.5 Average time taken to inspect each vessel
8.6 Quality and timeliness of intelligence information gathered

Potential Executor/Models. TTCP MAR AG-1 work with Queue Theory.

APPENDIX B.1: Vignettes/Vignette Variations of Specific National Interest

Vignettes or vignette variations of specific national interest are presented here for the reference of the group. In addition to informing specific national studies, it may be that these vignettes are more useful to the group than the generalized ones shown in the main body of the text.

Australian Phase 5 – AAW/ASMD Vignette

Issues of Australian interest:

- Performance of ASMD (PAR + IRST) ANZAC in point defense role in a FORCEnet/non-FORCEnet environment? (Needs heads-up on what the leakers are, FORCEnet vs. link)
- High-jamming environment? – if FORCEnet isn't being jammed ANZAC IRST picture being passed to coalition via FORCEnet, link 16
- ASMD project might want to be very FORCEnet compliant if IRST provides significant benefit to Force level ASMD
- AWD contribution to FORCEnet? Local Air Warfare Commander to protect NSFS ships (While CG is protecting ESG)

Vignette Description

During the AW phase there are two task groups. The first being the main task group lead by the U.S. Navy which includes a LHD/CVF and the second task group lead by RAN Air Warfare Destroyer (AWD), who is the Local Air Warfare Commander, with 2 x FFH are preparing for NSFS and Land Attack operations approximately 30 nm from the main task group. The main task group is under attack from multiple air threats consisting of sub-sonic and super-sonic ASMs launched from a hostile task group consisting of a number of SU-27s. Elements of this hostile task group split off and attack the Australian task group. Subsequently, the Australian task group is under attack from 8 sub-sonic and 4 super-sonic ASMs.

MOE/MOPs

- Probability of achieving raid annihilation
- Quality of Recognized Air Picture (RAP) between Local Air Warfare Commander (LAAWC) and Air Warfare Commander (AAWC)
- Handover of threats from AAWC to LAAWC
- AWD conduct as LAAWC
- FFH ASMD capabilities
- AWD ASMD/AAW capabilities

ORBAT

Blue Force ORBAT
U.S. led task group:
1 x U.S. CVN
2 x U.S. CG
1 x UK DDG

2 x CAN FFH
1 x U.S. E-2C

RAN task group:
1 x AS AWD
2 x AS ANZAC FFH

Red Force ORBAT
8 x SU-27

Information Requirements
(References to Table 3's force capability options are shown in brackets after each heading in the following.)

No FORCEnet (option I)
Link only (can't fire on someone else's track, FCR/IRST cueing or decoy employment only)

Intermediate FORCEnet (option II)
filtered, delayed, low BW (dialup) FORCEnet (like "no FORCEnet", but higher fidelity/faster updates)

Full FORCEnet (option III)
U.S. equivalent (CEC everywhere)

Example Storyboard
TBD by U.S., based on vignette description. (See also, NPS Study "FORCEnet for Coalition Joint Task Force, June 2005, TACSIT 2

Study Output Opportunity
SEA 4000, SEA 1448, JP 2048

Australian Phase 8 - Maritime Interception Operations

Vignette Description
Within Operation Philippine Comfort, separatist insurgents are using small boats, fishing vessels, etc. to transport personnel, weapons, drugs (for revenue-raising), and other suspicious materiel between the islands to disrupt coalition operations. With U.S. Navy assets occupied elsewhere, RAN/coalition units are tasked with intercepting insurgent vessels. The aim of the mission is to prevent transport of personnel, weapons, drugs, and to gather intelligence on insurgent operations.

MOE/MOPs
- Number of Critical Contacts of Interest (CCOI) successfully inspected vs. total number of craft in the AO
- Percentage of correctly identified CCOI in the Recognized Maritime Picture (RMP)

- Percentage of CCOI missed by the MIO
- Number of incorrectly identified craft boarded
- Average time taken to inspect each vessel
- Quality and timeliness of intelligence information gathered

ORBAT
Blue Force ORBAT
2 x AS ANZAC FFHs, with 2 x RHIBS and boarding teams
2 x FFs, with 2 x RHIBS and boarding teams

Red Force ORBAT
Insurgents potentially utilising:
Up to 50 fishing boats
10 small craft/coastal traders
4 large merchants

Neutral Force ORBAT
Up to 50 fishing boats
10 small craft/coastal traders
4 large merchants
(Legitimate craft, possibly transporting refugees from disaster areas

Information Requirements

- Intel reports, and Situation Awareness (RMP) from U.S. sensors
- Considerations of timing of information
- with/without link 16
- Fusion of organic and coalition information (handover of CCOI tracks from aircraft/satellite)

(References to Table 3's force capability options are shown in brackets after each heading in the following.)

No FORCEnet (option I)
2 x AS ANZACs (get filtered RMP via GCCSM/Centrixs)
2 x FFs (get filtered RMP via GCCS-M/Centrixs)

Intermediate FORCEnet (FFs option I, ANZACs option II)
2 x AS ANZACs (Fully FORCEnet capable: they get the U.S. COP (RMP)
2 x FFs (non-fully FORCEnet-capable coalition units: they get an RMP transfer from the AUS units

"Full FORCEnet (option III)
2 x AS ANZACs (Fully FORCEnet capable: they get the U.S. COP (RMP)
2 x FFs (Fully FORCEnet capable: they get the U.S. COP (RMP)

Example Storyboard
“Actionable intelligence”

1. Land-based assets track suspected insurgent leader/arm shipment to local port
2. Ascertain three small boats being used for island transfer
3. Potential track will take them through the MIO AO
4. Air asset assigned to conduct surveillance.
5. Tracks the three boats departing port
6. Air asset hands over tracking of contacts to MIO units upon entering MIO AO
7. MIO units track and conduct boarding of the three vessels
8. Contraband and leader discovered during search
9. All SITREPS passed via FORCEnet
10. FORCEnet used to disseminate info to Officer in Tactical Command (OTC) (probably U.S.) for determination of outcome

5,6,7,9, and 10 would be affected by different levels of FORCEnet compliance.

“Routine Boarding”

Same as 1.5.1 but without air asset, i.e.:

5. MIO force is conducting routine MIO in the AO

5.5. Land assets transfer all available info on CCOIs to MIO forces (via FORCEnet)

6. MIO detects CCOIs
7. MIO units track and conduct boarding of the three vessels
8. Contraband and leader discovered during search
9. All SITREPS passed via FORCEnet
10. FORCEnet used to disseminate info to OTC (U.S.) for determination of outcome

Study Output Requirements

Bandwidth requirements
Feed into Comms projects? [Action Group 6 of the TTCP, 2005]

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LIST OF REFERENCES

1. [Ali I, Bonanni P, 2002]. Ali, Irfan & Bonanni, Pierino, (2002). Doppler Applications in LEO Satellite Communication Systems. Boston: Kluwer Academic Publishers.

2. [Action Group 6 of the TTCP, 2005]. Coalition FORCEnet Study – Operation Philippine Comfort Scenario.

3. [Andrews L, 2005]. Andrews, Lisa, ORBIMAGE 2005, ORBIMAGE Selected as NGA's Second NextView Provider. Retrieved April 22 from http://www.orbimage.com/news/releases/09-30A-04.html

4. [Barnes JM, Santoro RT 1988]. Barnes J.M., Santoro R.T. (1988) Shield Optimization Program, Part 2: Effects of Van Allen Belt Radiation on SDI Weapon Platforms. Report # A258443. Retrieved June 2006 from http://www.stormingmedia.us/25/2584/A258443.html

5. [Brown C, 2002]. Brown, Charles (2002). Elements of Spacecraft Design. American Institute of Aeronautics and Astronautics Inc.

6. [Bussieres, Goita 1997]. Bussieres and Goita 1997 Evaluation of strategies to deal with cloudy situation in satellite evapotranspiration algorithm. Proceeding of the Third International Workshop NHRI Symposium 17, 16-18 October 1996, NASA, Goodard Space Flight Center, Greenbelt Md USA 33-43

7. [Davis, 2006]. Davis, Thomas M., and Straight, Capt. Stanley,"Development of the Tactical Satellite 3 for Responsive Space Missions", AIAA-LA Section/SSTC Responsive Space Conference 2006, Paper 2006-4003.

8. [Dewey RG, Bishop J 2005]. Dewey, R.G. & Bishop, J. (2005, October). Common Data Link from Space - Preliminary Lessons from the TacSat-2 Demonstration Program. *Military Communications Conference, MILCOM 2005,* 1-7.

9. [Doyne, 2006]. Doyne, Col. Tom, et. al., "A TacSat and ORS Update Including TacSat-4", AIAA-LA Section/SSTC Responsive Space Conference 2006, Paper 2006-4006.

10. [Dyer C, 2003]. Dyer, Clive (2003) Space Radiation Effects For Future Technologies and Missions, Report reference QINETIQ/KI/SPACE/TR010690/1.1. Retrieved 6/2006 from http://reat.space.qinetiq.com/Reat/wp1_tn/Document_text.html

11. [eoPortal 2006]. Data table retrieved 7-3-2006 from http://www.eoportal.org/

12. [Exec Sum]. Executive Summary of the Commercial Satellite Communications (SATCOM) Report

13. [EXPLAN, 2005]. Experimentation Plan (EXPLAN) For Terminal Fury 06 CPX Initiative: TacSat-1 OPERATIONS December 2005

14. [GAO-05-6]. GAO Report (November 2004). Report to the Chairman, Subcommittee on Tactical Air and Land Forces, Committee on Armed Services, House of Representatives; GAO-05-6

15. [Gkizeli et al, 1999]. Gkizeli, M., Taaghol, P., & Evans, B. G. (1999). Service Availability of LEO/MEO Mobile Satellite Systems. *International Journal of Satellite Communications, 17,* 291-302.

16. [Griffin M.D, 2004]. Griffin, Michael D. (2004) Space Vehicle Design Second Edition, Reston VA: AIAA ISBN 1-56347-539-1.

17. [Heki K., 2006]. HEKI, KOSUKE; Energy estimation of the 2004/Sep/1 Asama explosion with ionospheric disturbances Hokkaido Univ. Retrieved April 17, 2006 fromhttp://www.asiaoceania-conference.org/Abstract2006/AbstractFile%5CSE%5CSE30%5C59-SE-A0686.rtf

18. [Hirshfield E, 1996]. Hirshfield, E. (1996, May). The Globalstar system breakthroughs in efficiency in microwave and signal processing technology. *ELECTRO '96 Professional Program Proceedings,* 147-152.

19. [Hodge N, 2002]. Hodge, Nathan 2002. Space Imagery Challenged By Concealment, Terrain. Defense Week June 10, 2002

20. [Joint Pub, 2001]. Joint Publication 1-02. DoD Dictionary of Military and Associated Terms, 12 April 2001

21. [Justifying Sharp, 2006]. Justifying Sharp Global Hawk Price Increase; (May 24, 2006) Strategy Page. Retrieved June 22 from http://www.strategypage.com/htmw/htproc/articles/20060524.aspx

22. [Kolawole M, 2002]. Kolawole, Michael (2002). Satellite Communication Engineering. Marcel Dekker Inc

23. [L3, “ABIT”, 2006]. L3 Communications. Airborne Information Transmission System (ABIT) Collector Data Link. Retrieved June 10, 2006 from http://www.l-3com.com/csw/Product/docs/ABITcollector%20dl.pdf.

24. [L3, “Model-U” 2006]. L3 Communications. T-Series Model-U Airborne Data Link. Retrieved June 10, 2006 from http://www.l-3com.com/csw/Product/docs/03-T-Series%20Model%20U.pdf.

25. [L3, “Model-WB” Airborne 2006]. L3 Communications. T-Series Model – WB Airborne Data Link. Retrieved June 10, 2006 from http://www.l-3com.com/csw/Product/docs/01-T-SeriesModel-WB.pdf.

26. [L3, “Modular Interoperable” 2006]. L3 Communications. Modular Interoperable Surface Terminal (MIST). Retrieved from http://www.l-3com.com/csw/product/specs/Surface/MISTSpecs.asp.

27. [Larson W, Wertz J 1999]. Larson, Wiley & Wertz, James (1999). Space Mission Analysis and Design Third Edition. Microcosm Press Inc.

28. [Leachtenauer J, Driggers R 2001]. Leachtenauer, Jon & Driggers, Ronald (2001). Surveillance and Reconnaissance Imaging Systems-Modeling and Performance Prediction. Artech House.

29. [Loy H, 2005]. Loy, Huichieh (2005) The Politics of Disaster, From a Singapore Angle. Retrieved June 30, 2006 from http://singaporeangle.blogspot.com/2005/01/politics-of-disaster-relief-indonesia.html

30. [NDAA, 2006]. National Defense Authorization Act For Fiscal Year 2006 Report of the Committee On Armed Services House Of Representatives On H.R. 1815,109-89

31. [Optical Micro, 2006]. Optical Microscopy Primer, (2006). http://micro.magnet.fsu.edu/primer/digitalimaging/concepts/dynamicrange.html

32. [Olsen, R.C.2005] Olsen R.C. (2005) Remote Sensing from Air and Space. Naval Post Gradúate School.

33. [Optical Micro, 2006]. Optical Microscopy Primer, (2006). http://micro.magnet.fsu.edu/primer/digitalimaging/concepts/dynamicrange.html

34. [Pasternak D, 2003]. Pasternak, Douglas; "Lack of Intelligence" U.S. News and World Report August 11, 2003.

35. [Pease CB, 1991]. Pease, C.B. 1991 Satellite Imaging Instruments. Ellis Horwood Limited, England

36. [Perko K et al, 2002]. Perko, K., Huggins, R., Heisen, P., Miller, G., McMeen, D., Dod, T., et. al. (2002) X-Band Phased Array Antenna Validation Report. Retrieved June 26, 2006, from http://eo1.gsfc.nasa.gov/new/validationReport/Technology/Documents/Reports/XPAA.pdf.

37. [Pete M, Gardie J 1999]. Pete Mouginis-Mark (1), Jonathan Gradie 1999 Production of Cloud-Free Satellite Image Maps of Hazardous Volcanoes Science & Technology International, Honolulu, Hawaii

38. [Pike J, 2005]. Pike, J. (2005). Common Data Link [CDL]. Retrieved June 3, 2006, from http://www.globalsecurity.org/intell/systems/cdl.htm.

39. [Pratt et al, 2003]. Pratt, Timothy & Bostian, Charles (2003). Satellite Communications (2nd Edition). John Wiley and Sons.

40. [Ptak A, 1997]. Ptak, Andy (1997), Ask an Astrophysicist, *NASA GSFC*. Retrieved on 2006-06-11.

41. [Roy PS, Agarwal V 2006]. Roy, P. S., Agarwal, Vandana· FEB 2006. Technology trends in Remote Sensing and data analysis. GIS Development; Geospatial Resource Portal. Retrieved April 19 from http://www.gisdevelopment.net/technology/rs/techrs0018.htm

42. [RQ-4 Global Hawk]. RQ-4 Global Hawk: Encyclopedia. Retrieved June 26 from http://experts.about.com/e/r/rq/RQ-4_Global_Hawk.htm

43. [Sarabhai V]. Sarabhai, Vikram; Department of Space, Indian Space Research Organization, Indian Satellites. Retrieved April 21 from http://www.isro.org/sat.htm

44. [Sleeth D, 2004]. Sleeth, Denette L. FEB 9, 2004; NAVAL WAR COLL NEWPORT RI JOINT MILITARY OPERATIONS DEPT. Commercial Imagery Satellite Threat: How Can U.S. Forces Protect Themselves? Report number A057224

45. [SMAD]. Wertz, R and Larson, Wiley. Space Mission Analysis and Design. Space Technology Series. United States Department of Defense and National Acronautics and Space Administration.

46. [Space Today]. Space Today. Retrieved July 6 from http://www.spacetoday.org/Rockets/Spaceports/LaunchSites.html#Andoya

47. [Tascione T.F., 1994]. Tascione, Thomas F. (1994). *Introduction to the Space Environment, 2nd. Ed.*. Malabar, Florida USA: Kreiger Publishing CO.. ISBN 0-89464-044-5.

48. [Tomme. E. 2006]. Tomme. Edward. LtCol (ret) (2006). The strategic Nature of the Satellite. Sci-Ops Consulting, Inc white paper.

49. [UAV Forum]. UAV Forum. Retrieved June 15, 2006 from http://www.uavforum.com/library/librarian.htm

50. [Wertz J, Van Allen R 2006]. Wertz, James and Van Allen, Richard (2006)/ Aggressive Surveillance as a Key Application Area for Responsive Space. 4th Responsive Space Conference April 25, 2006.

51. [Wood et al]. Wood, Lloyd, Shell, Dan, Miller, Eric, Ivancic, Will, Stewart, Dave, Conner, Brett, Hodgsin, Dave, CLEO and VMOC Enabling Warfighters to Task Space Payloads

52. [Wood, L 1999]. Big LEO Tables Retrieved 7-8-2006 from (http://www.ee.surrey.ac.uk/Personal/L.Wood/constellations/tables/tables.html)

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